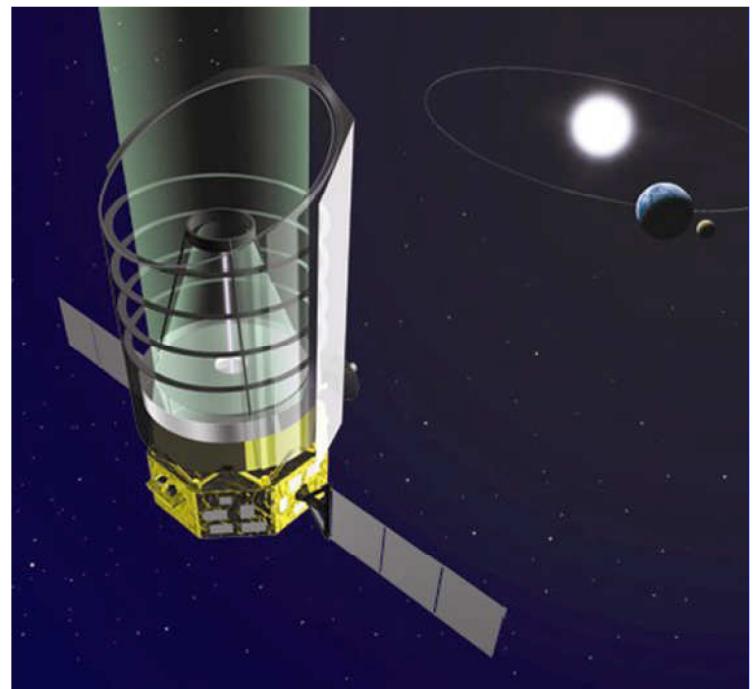
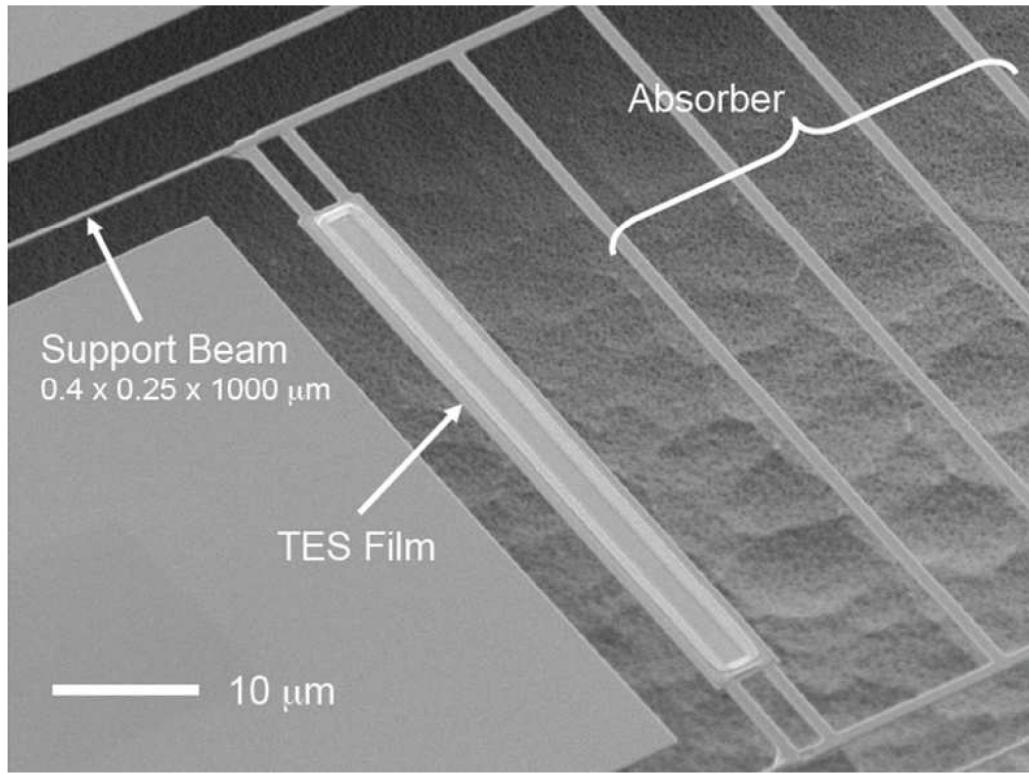


# Achieving BLISS: Challenges for building fast, ultra-sensitive transition-edge sensors



**Andrew D. Beyer<sup>1</sup>, M. C. Runyan<sup>2</sup>, M. Kenyon<sup>1</sup>, P.M. Echternach<sup>1</sup>, T. Chui<sup>1</sup>,  
B. Bumble<sup>1</sup>, C.M. Bradford<sup>1,2</sup>, W.A. Holmes<sup>1</sup>, and J.J. Bock<sup>1,2</sup>.**

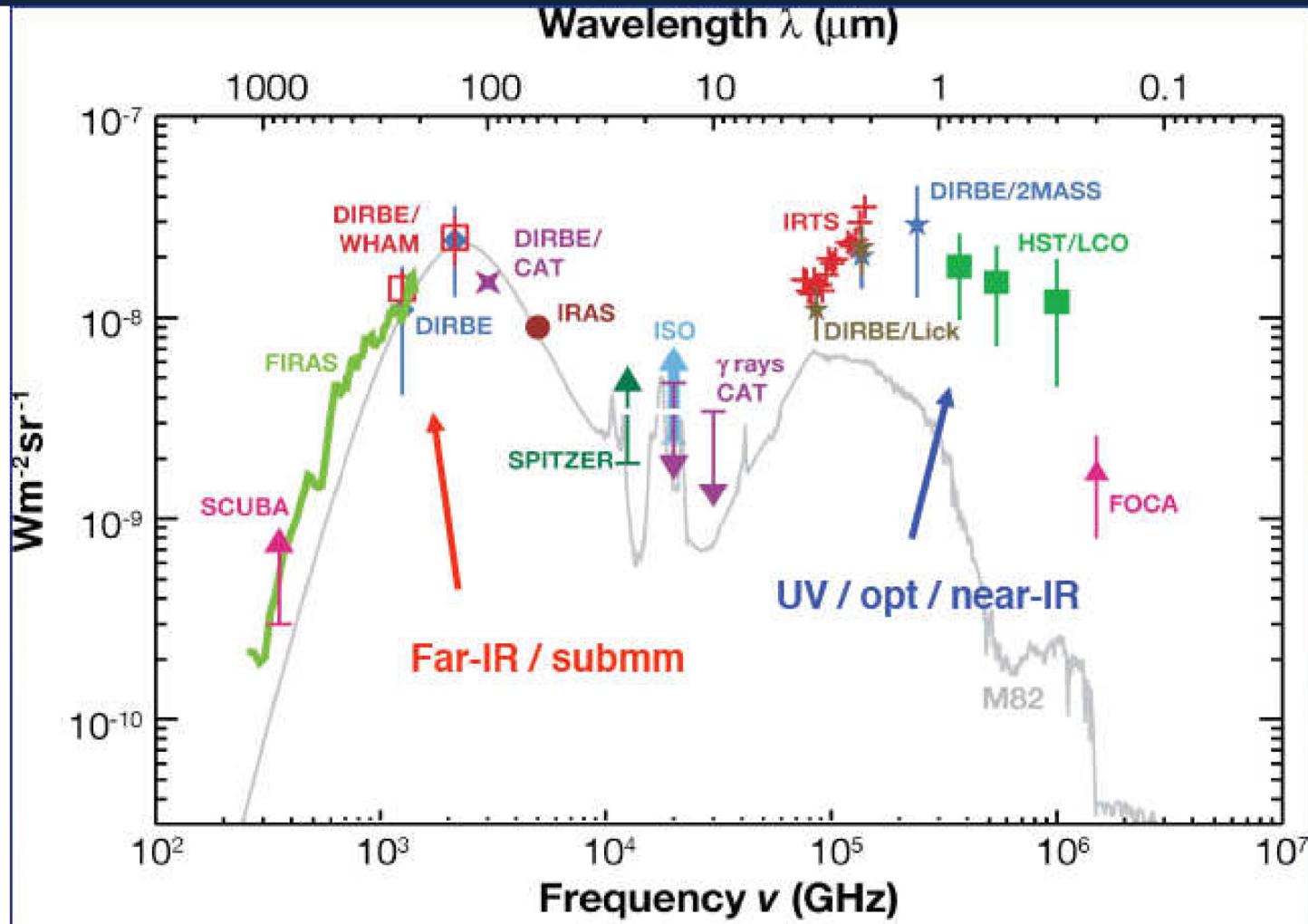
<sup>1</sup> Jet Propulsion Laboratory, Pasadena, CA, USA.

<sup>2</sup> California Institute of Technology, Pasadena, CA, USA.

# Outline

1. Motivation and intro to TESs.
2. BLISS Specifications—tolerance to dark power
3. Measuring stray (dark) power— $T_c$  (alpha) and G measurements
  - a. Overview two methods: JTD vs. TES
  - b. TES arrays: measurement complications for  $P_d$ ,  $T_c$ , and alpha.
4. Results:  $P_d$  compare, NEP, tau, 1/f issues

# Extragalactic background light

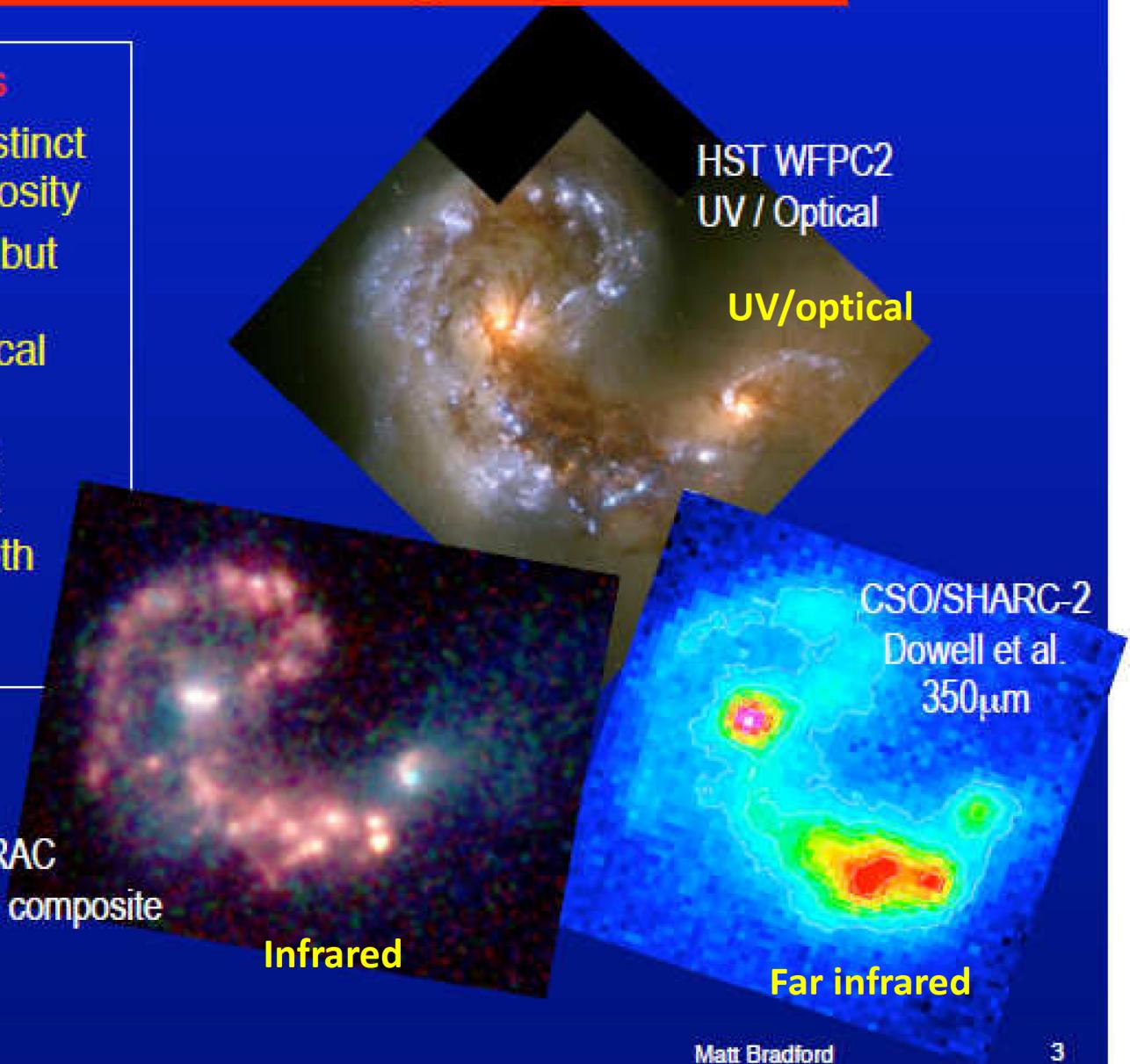


- $\frac{1}{2}$  is in the far-IR.
- Hidden evolution: dust-obscured star formation, black-hole growth.

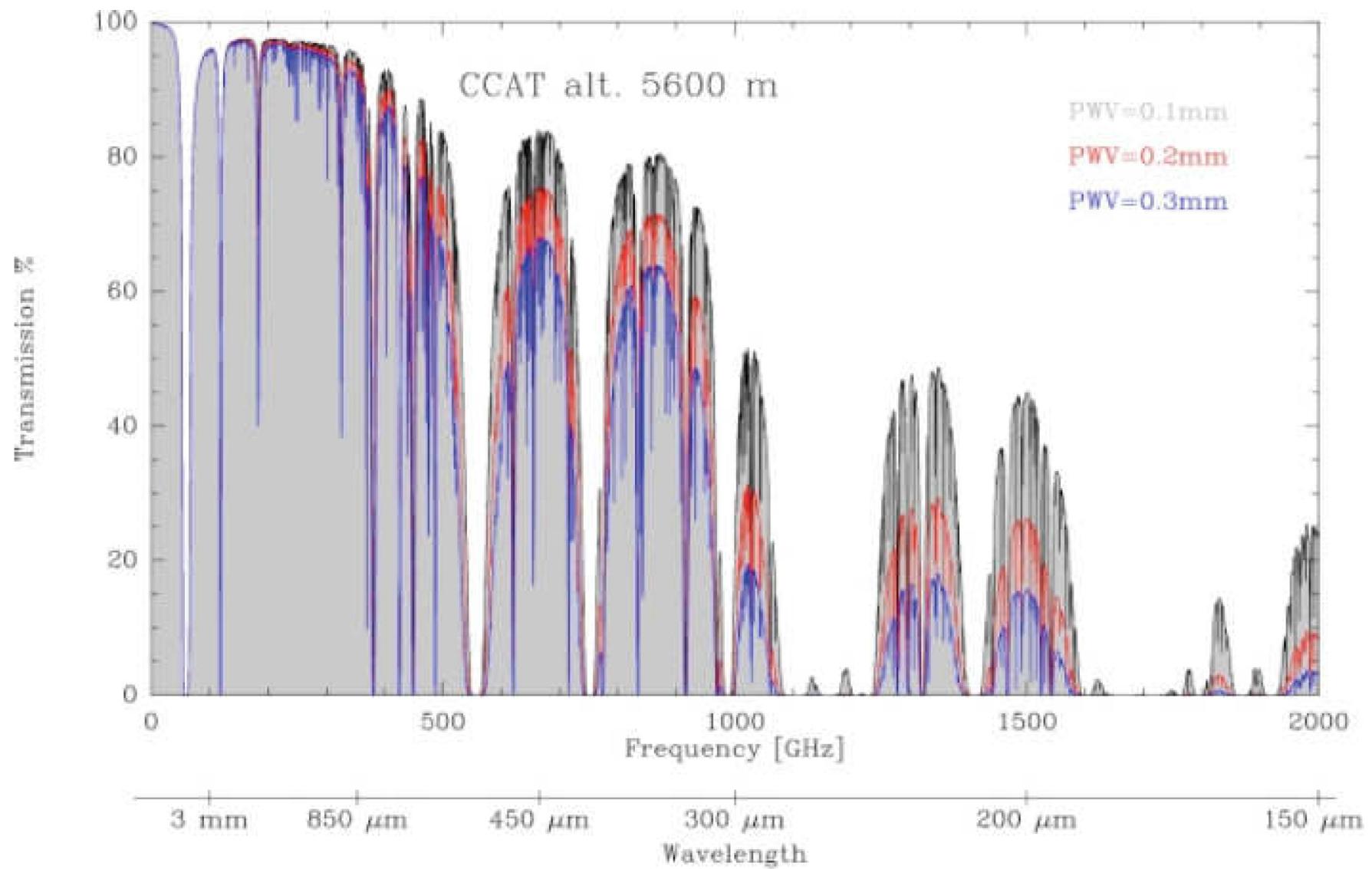
# A class of entire galaxies emit the bulk of their radiation in the far-IR -- e.g. The Antennae

## LIRGs and ULIRGs

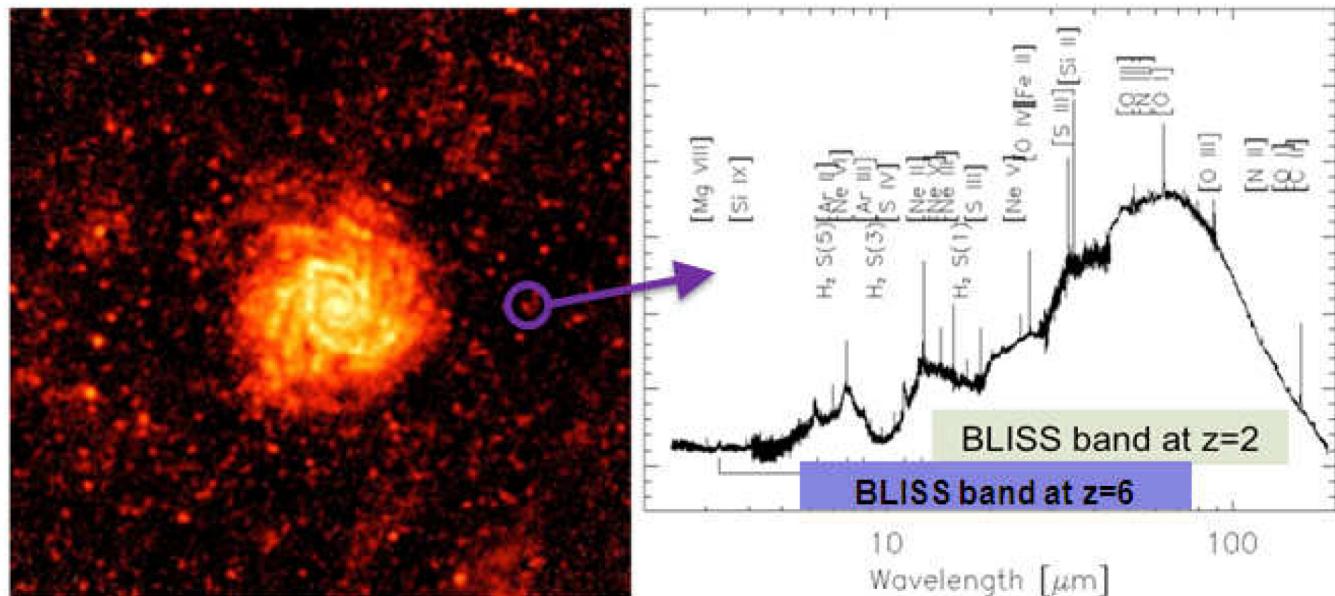
- Excellent example of distinct optical/UV and IR luminosity
- Interaction long known, but huge luminosity is not predicted based on optical studies
  - >90% of the energy is emitted at in the far-IR
- Large luminosity has both starburst and accretion components



# Far-IR/sub-mm measurements from Earth?



# A long time ago in a galaxy far, far, away...



**Left:**

-Herschel/SPIRE image of M74 observed at 250  $\mu\text{m}$ .

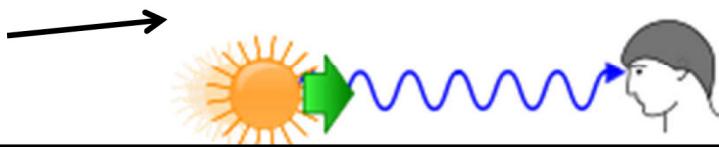
**Right:**

- Infrared Space Observatory (ISO) spectrum of the Circinus galaxy, a nearby analogue of the galaxy in the SPIRE image.

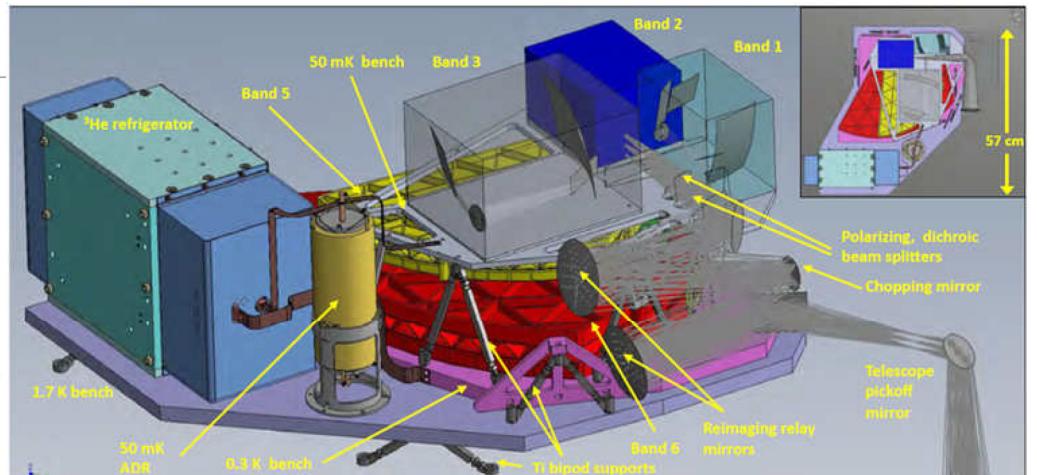
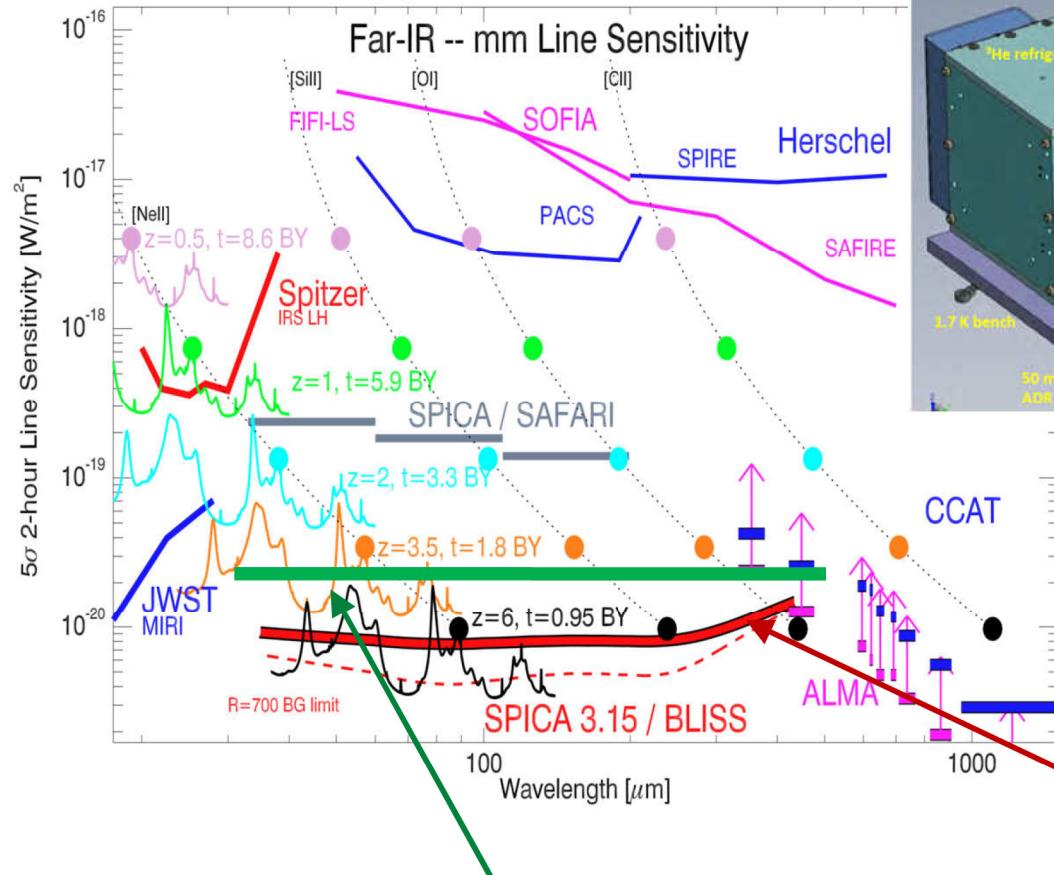
**BLISS:** will see back to the 1<sup>st</sup> billion years.



**Redshift (z)** is related to the distance of an object from us → larger z implies an object farther away than smaller z.



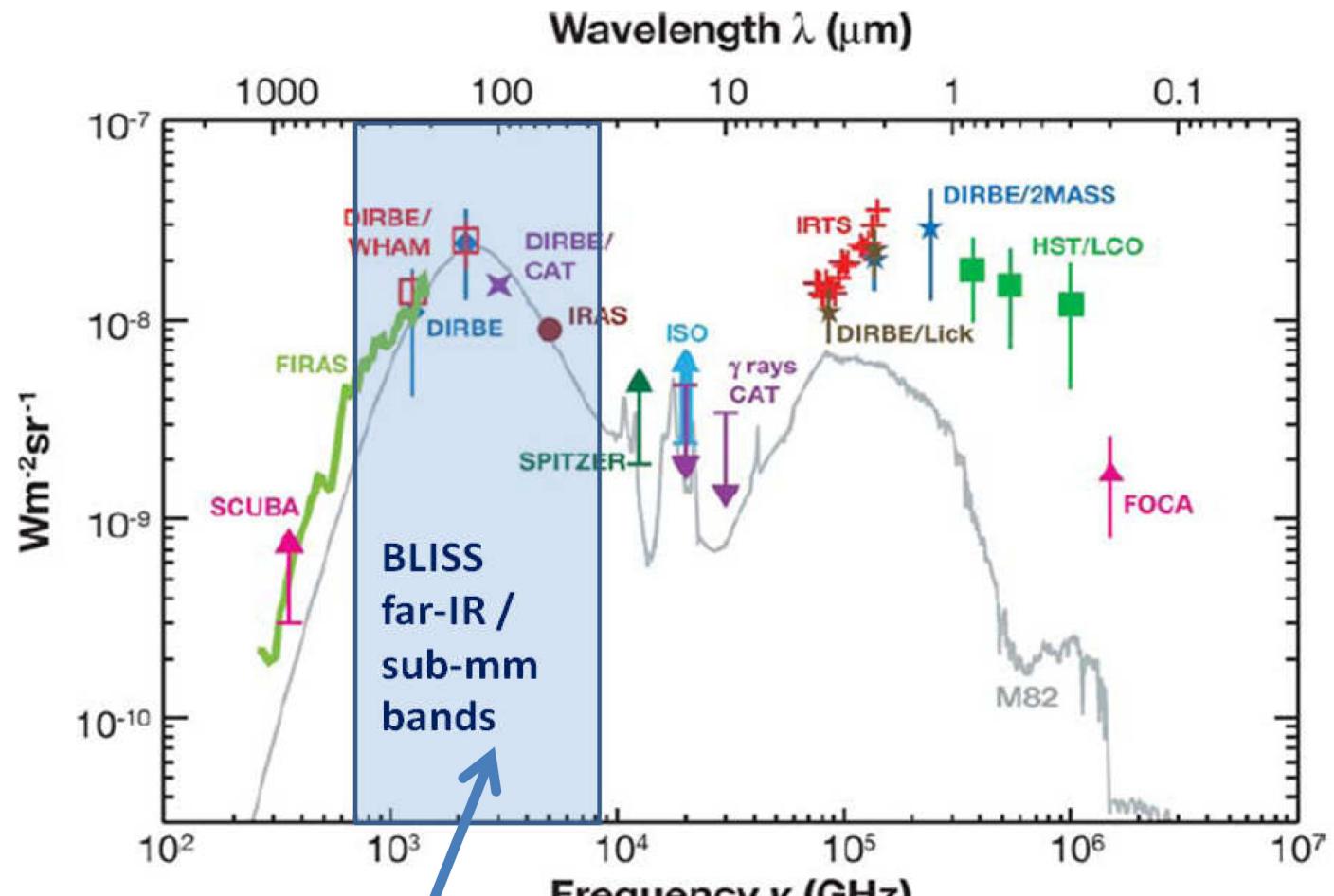
# BLISS for SPICA



- Sensitive wideband grating spectrometer.
- 6 bands to cover 35-433  $\mu\text{m}$  at  $R \sim 700$ .
- Baseline 4224 TES bolometers at 50 mK with time-domain SQUID MUX.

- Desired sensitivity: **2e-20 W m<sup>-2</sup> (5s, 2h) for Requirement** and **1e-20 W m<sup>-2</sup> for Goal** under conservative assumptions (photons contributing equally at goal sensitivity).
- **Detector noise equivalent power (NEP): Requirement: 1e-19 W Hz<sup>-1/2</sup>, Goal: 3e-20 W Hz<sup>-1/2</sup>**

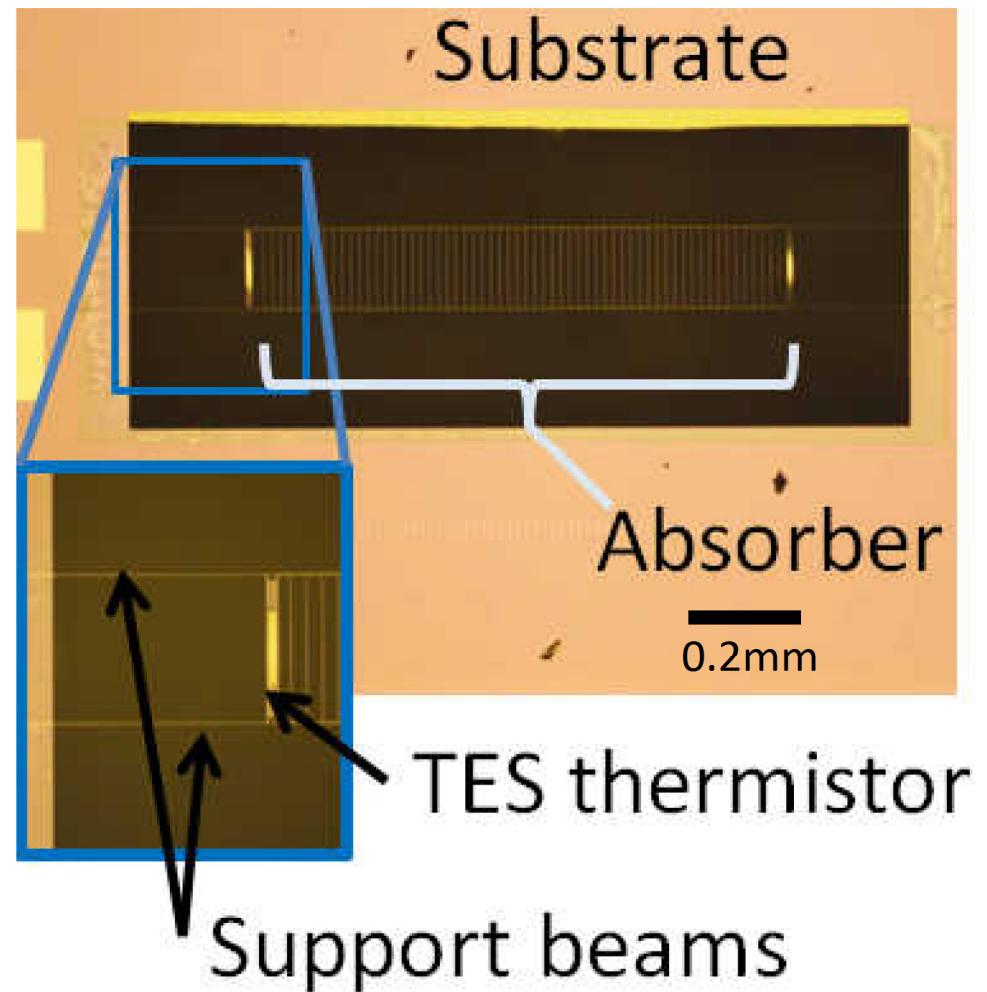
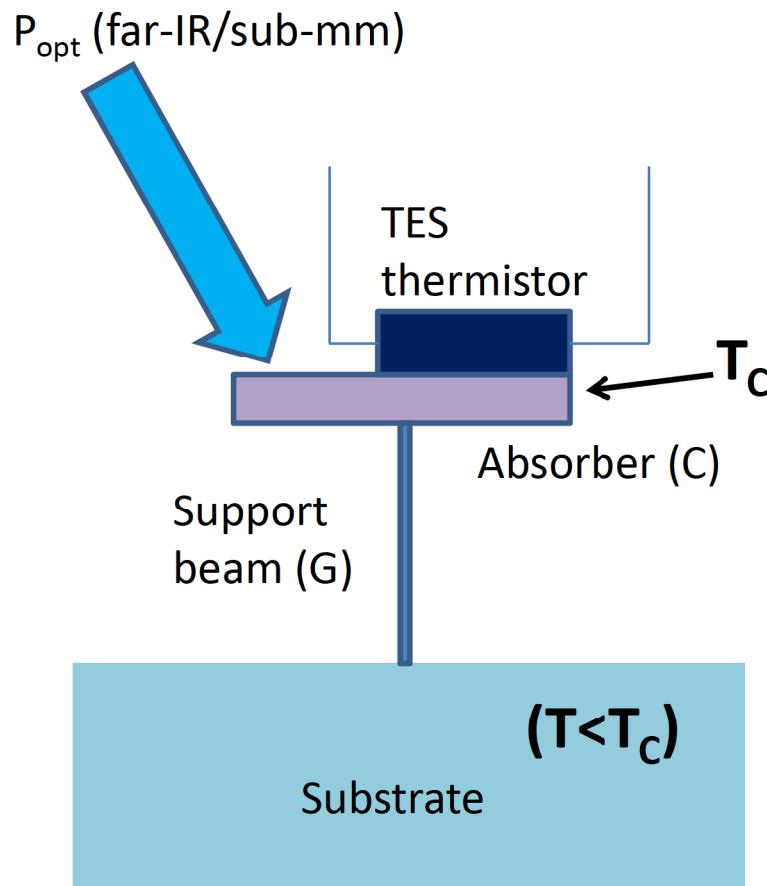
# BLISS: Far-IR/sub-mm in space



Extragalactic background light:

- ½ is in the far-IR.
- Hidden evolution: dust-obscured star formation, black-hole growth.

# Transition-edge sensors (TESs) for BLISS



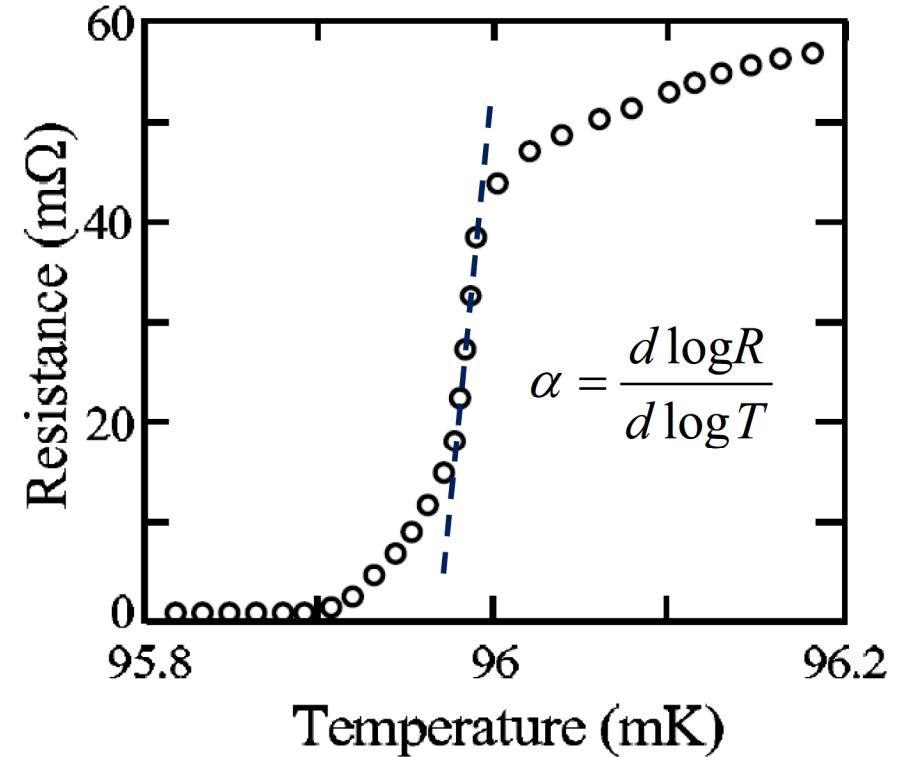
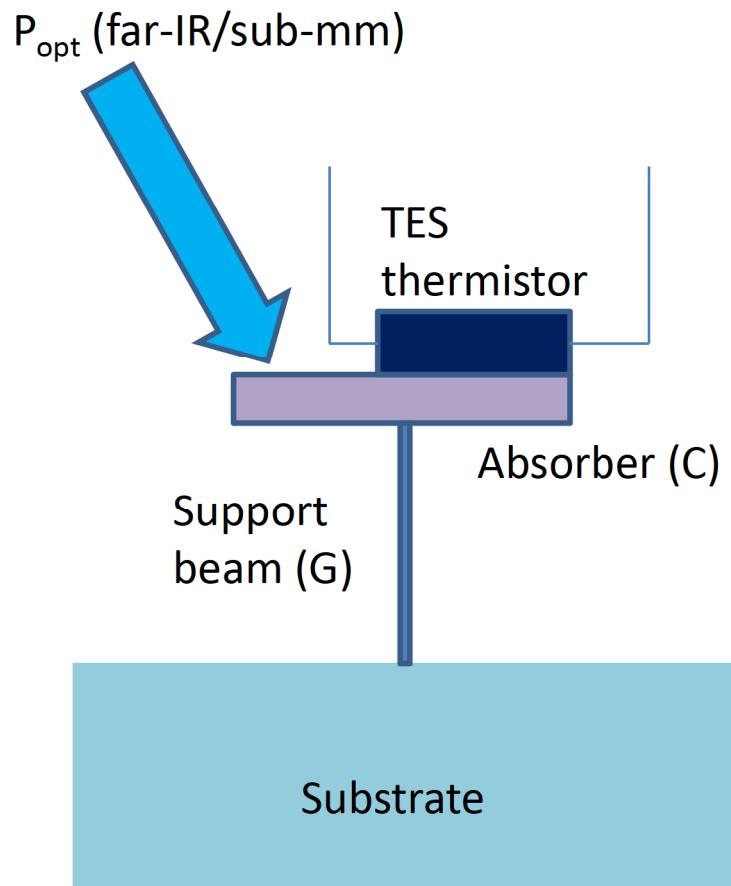
**TES:** transition-edge sensor.

**G:** thermal conductance.

**C:** Heat capacity.

**$T_c$ :** superconducting transition temperature.

# Transition-edge sensors (TESs) for BLISS



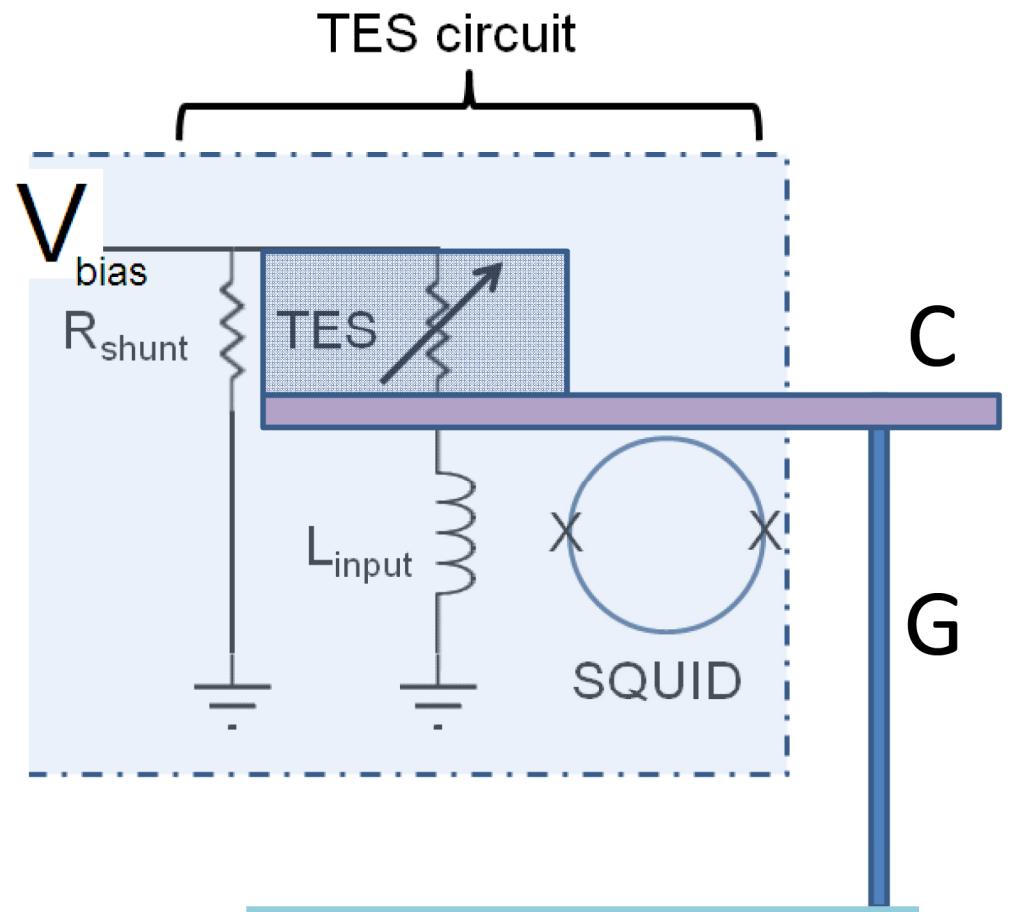
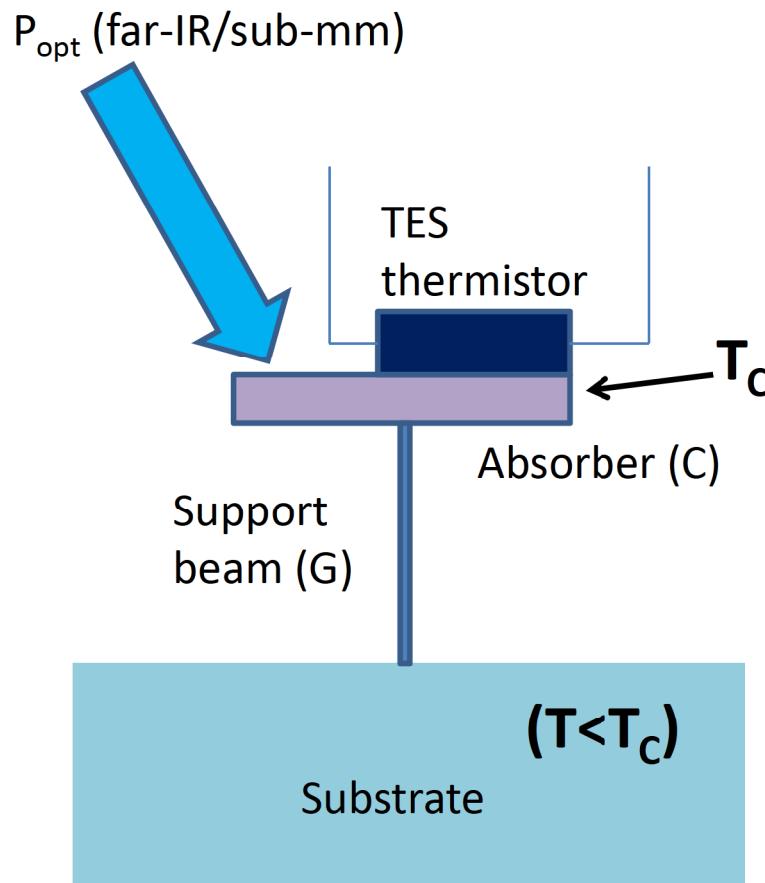
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# Transition-edge sensors (TESs) for BLISS

**Goal:** sense power on TES in far-IR/sub-mm.

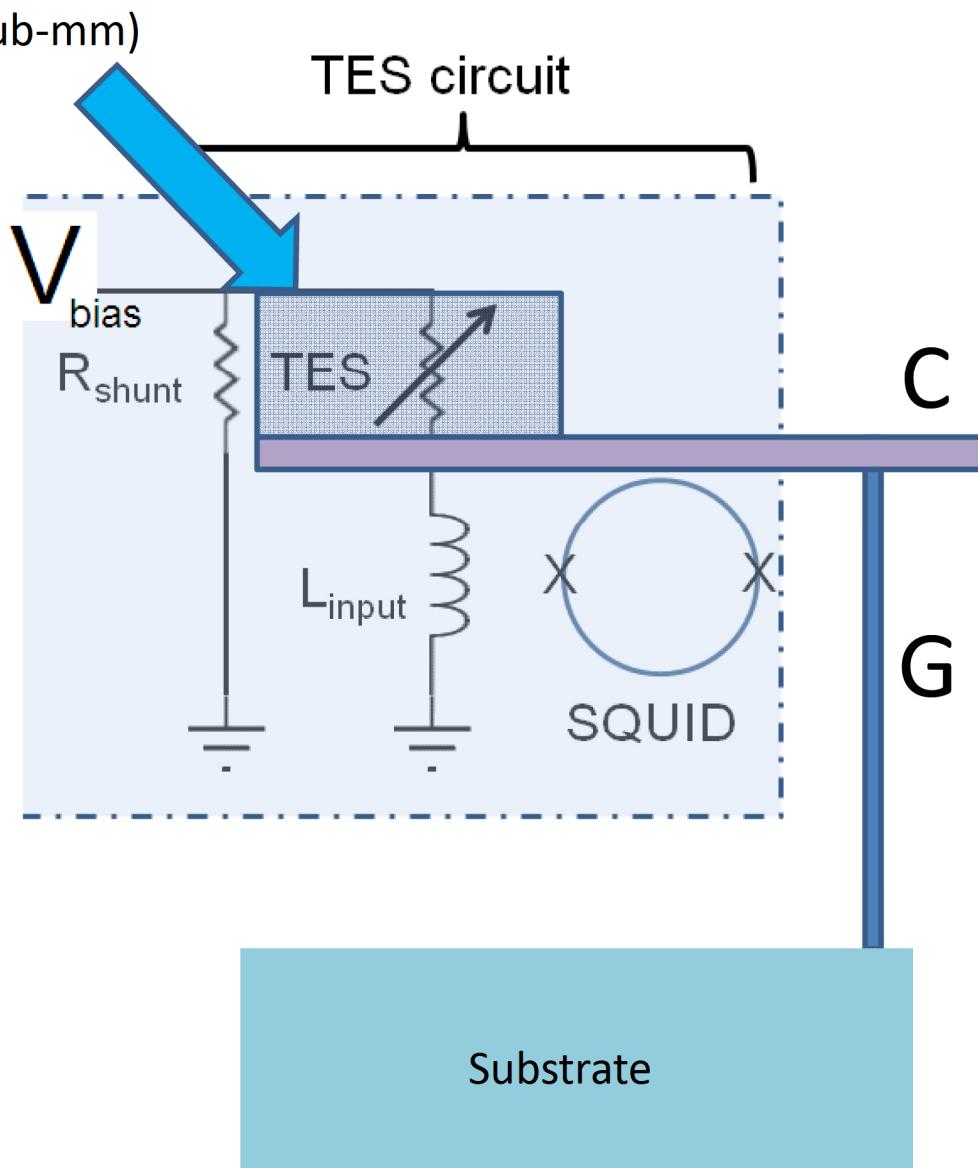
**Noise sources (W/Hz<sup>1/2</sup>) :**

Photon noise,

Resistors (Johnson noise),

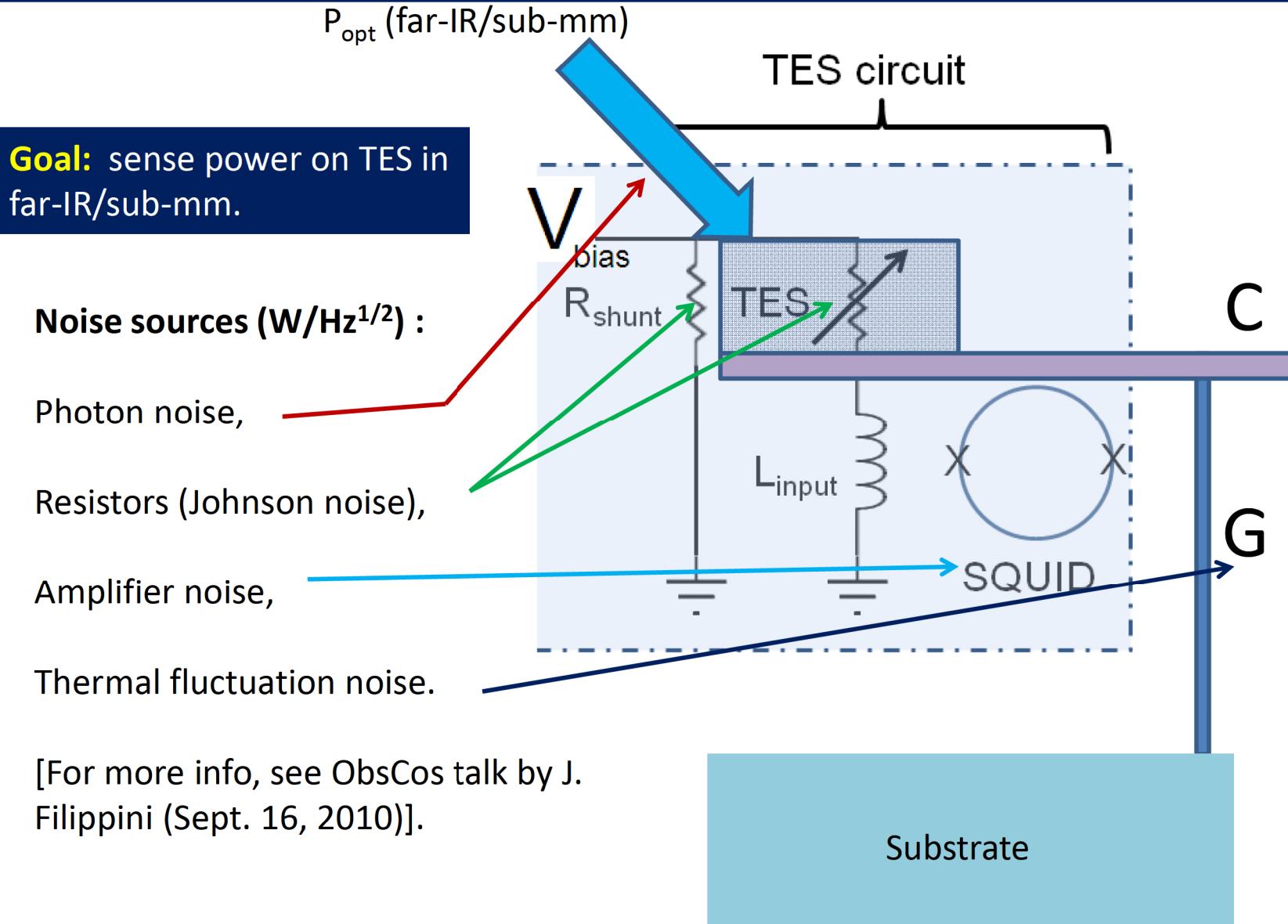
Amplifier noise,

Thermal fluctuation noise.



TES: transition-edge sensor.

# Transition-edge sensors (TESs) for BLISS



[For more info, see ObsCos talk by J. Filippini (Sept. 16, 2010)].

TES: transition-edge sensor.

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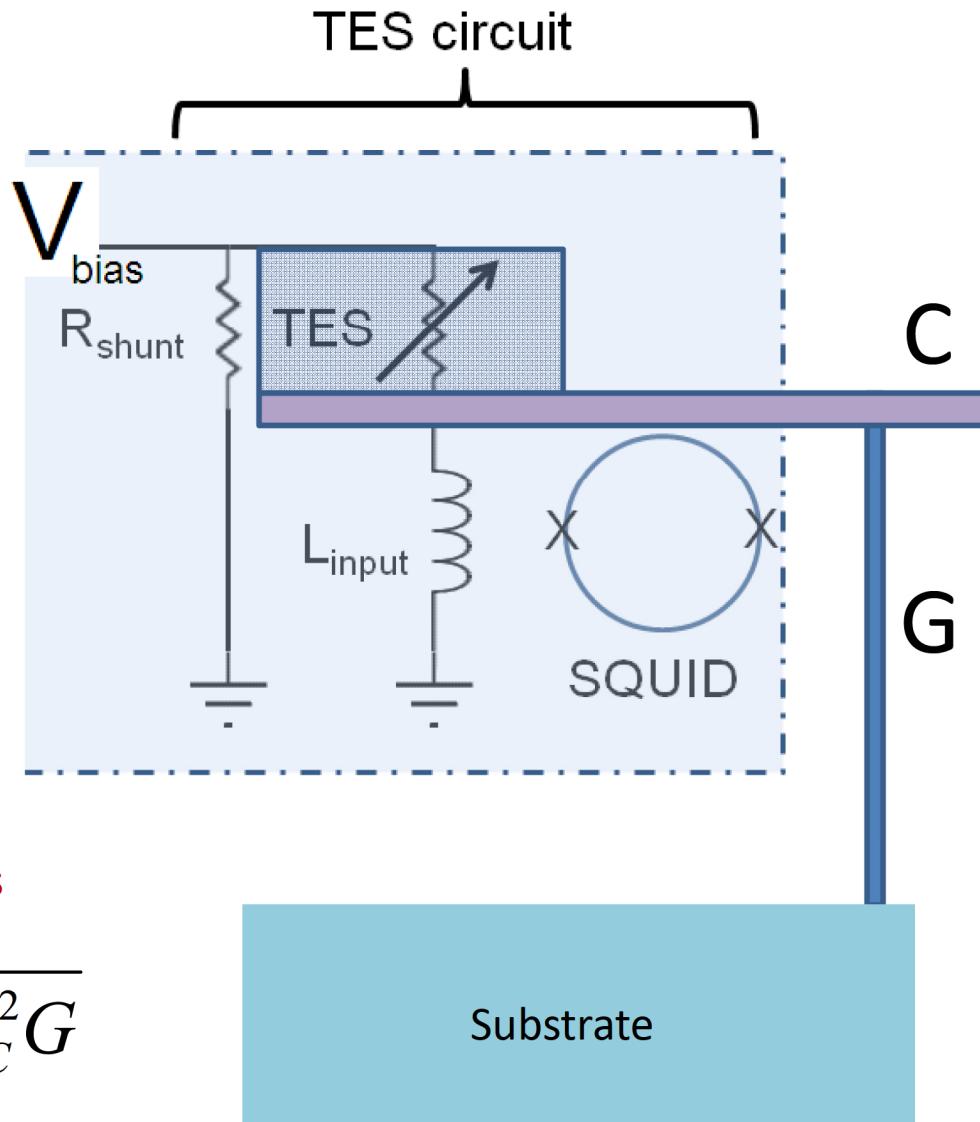
Resistors (Johnson noise),

Amplifier noise,

Thermal fluctuation noise.

dominates

$$NEP_{TFN} = \sqrt{4k_B T_C^2 G}$$



TES: transition-edge sensor; NEP: noise equivalent power.

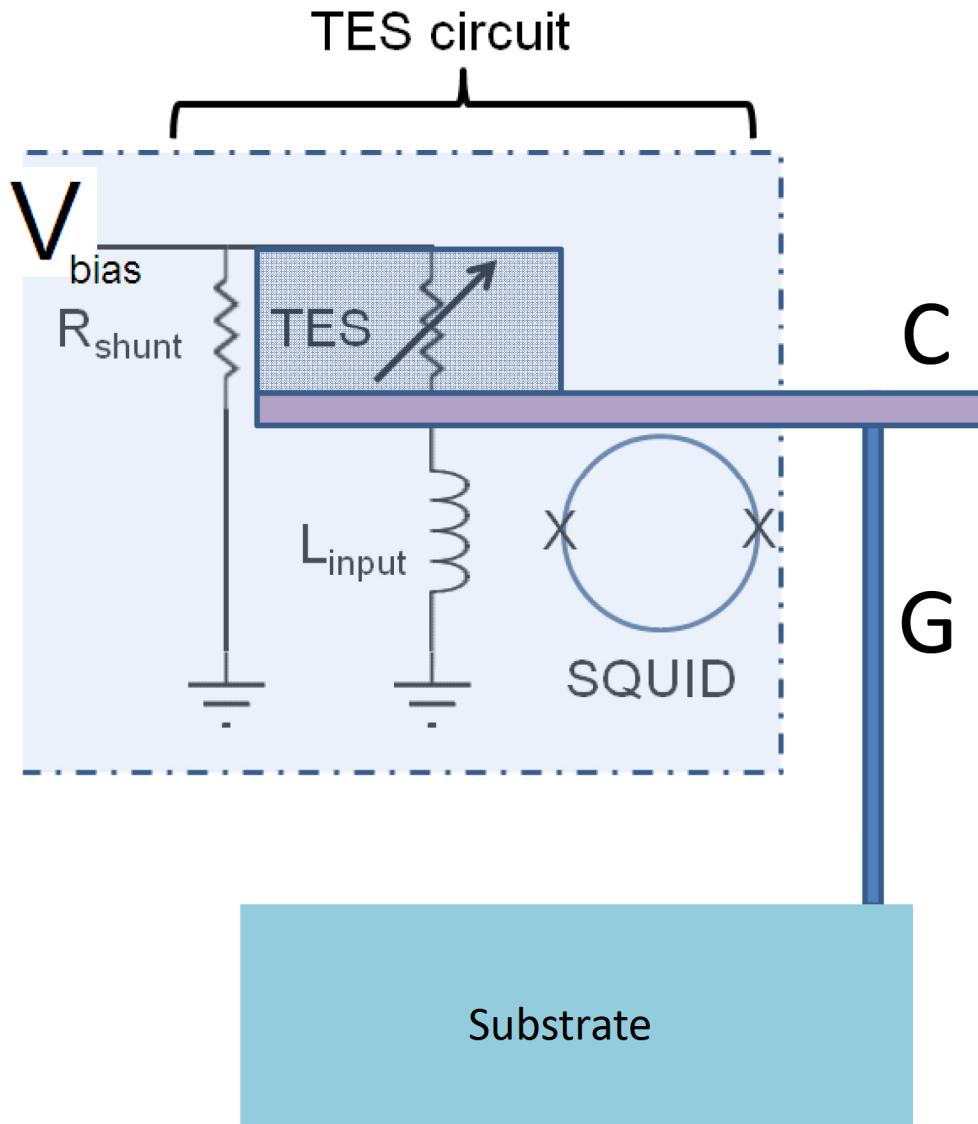
# Transition-edge sensors (TESs) for BLISS

**Goal:** sense power on TES in far-IR/sub-mm.

**Response time:**

$$\tau_0 = C / G$$

$$\tau = \frac{\tau_0}{1 + \frac{P_J \alpha}{G T_C}}$$

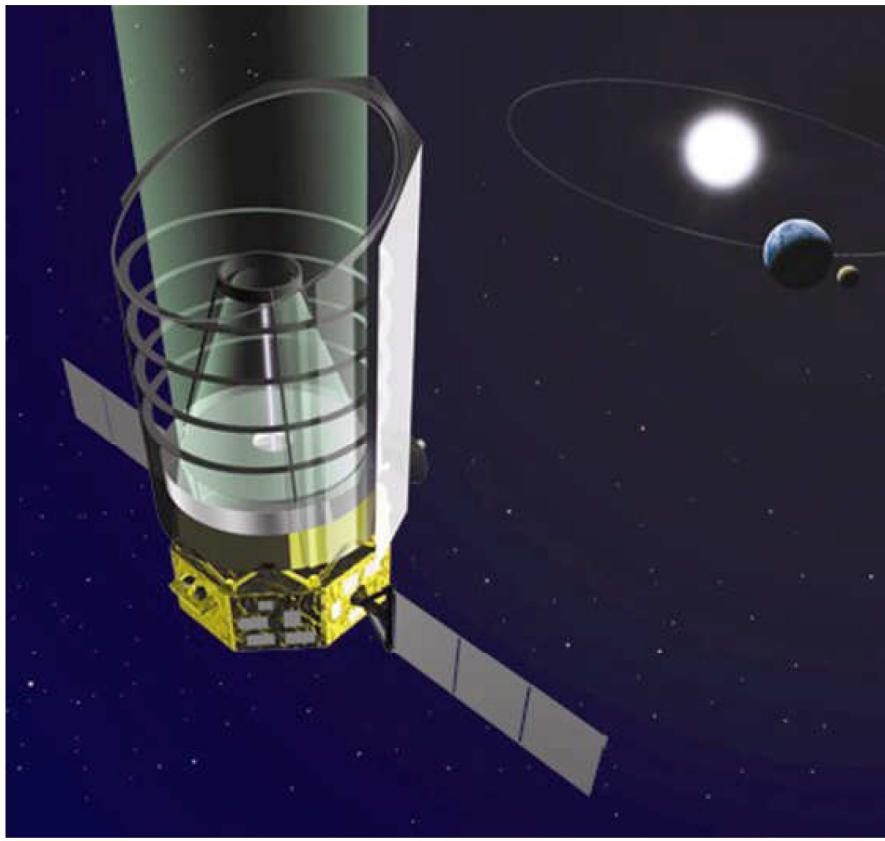


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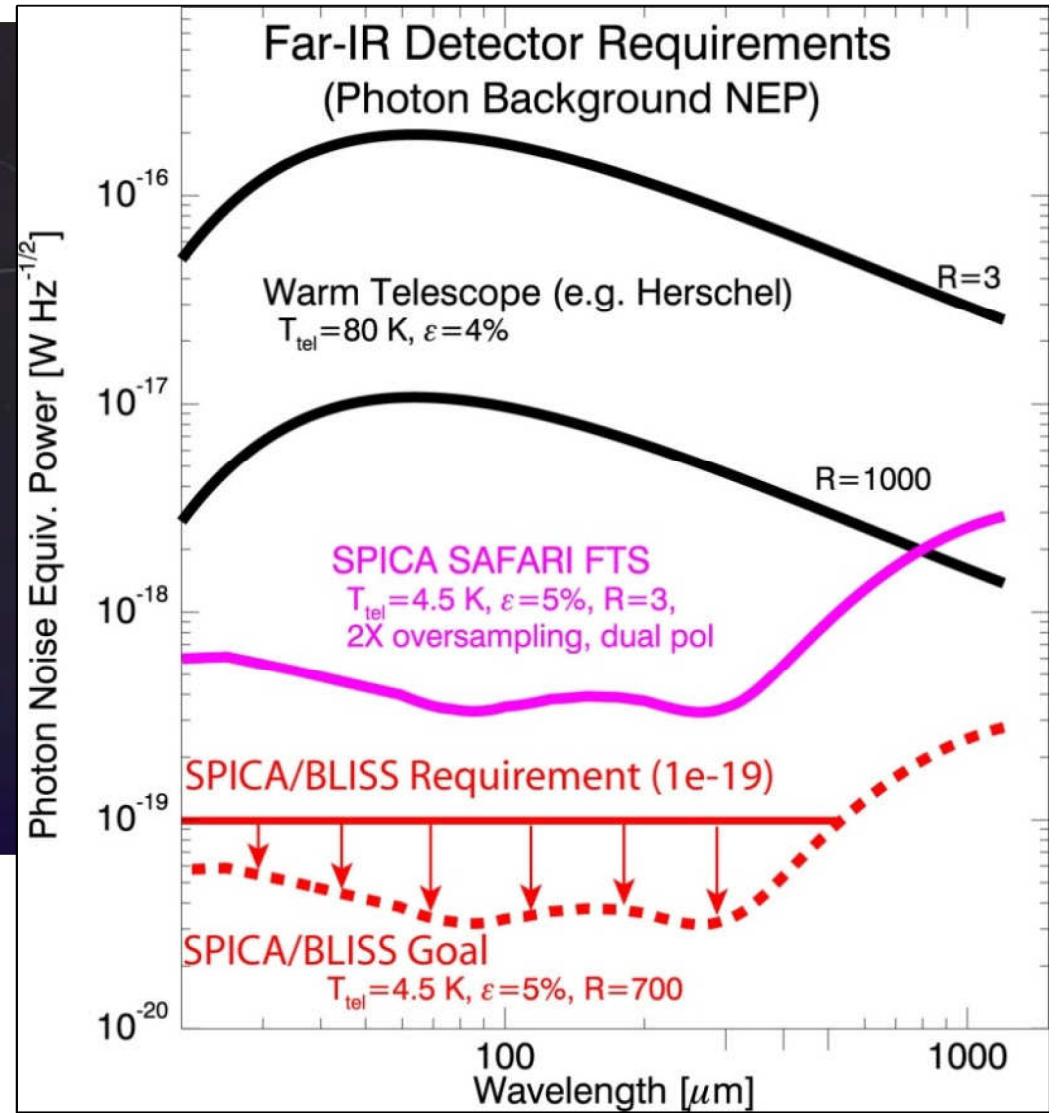
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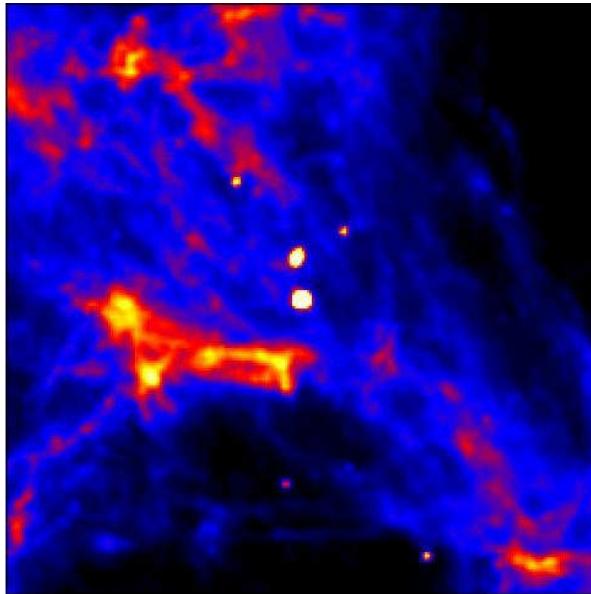
# SPICA—the first large cryogenic observatory



- Size: 3.5m .
- $T=4.5\text{ K}$ .
- Optimized for 10 to  $600\mu\text{m}$  observations.



# BLISS design goal parameters



**Galactic cirrus:** Image Credits:  
Infrared Processing and Analysis  
Center, Caltech/JPL. IPAC is NASA's  
Infrared Astrophysics Data Center.

## Loads on bolometer:

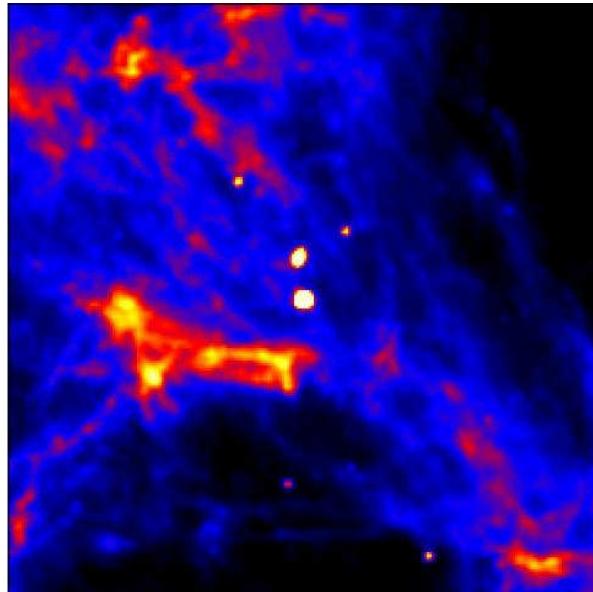
-Zodiacal light, galactic cirrus,  
CMB, telescope, baffles.

Estimated power load at  
bolometer

Band ( $\mu\text{m}$ )	( $\mu\text{m}$ )	357	230	148	92	53
Safety factor		75	150	200	400	400
$P_{\text{bolometer}}$	(aW)	2.29	0.34	0.25	0.13	0.12
$P_{\text{sat.}}$	(aW)	172	51	49	52	50
C	(fJ/K)	13	13	13	13	13
G	(fW/K)	12	4	4	4	4
C/G	(s)	1.07	3.63	3.71	3.49	3.69
$\tau$	(s)	0.05	0.16	0.16	0.15	0.16

- Base temperature = 50mK,  $T_c = 65\text{mK}$ .
- Thermal conductance G is chosen so that  $\text{NEP}_{\text{detector}}$  matches  $\text{NEP}_{\text{photon}}$ .
- Heat capacity C expected from Si-N → suitable speeds for chosen G values.
- G, C shown for NEP goal. For BLISS NEP requirement  $G \rightarrow G \times 10$ ,  $C \rightarrow C \times 10$ .

# BLISS design goal parameters



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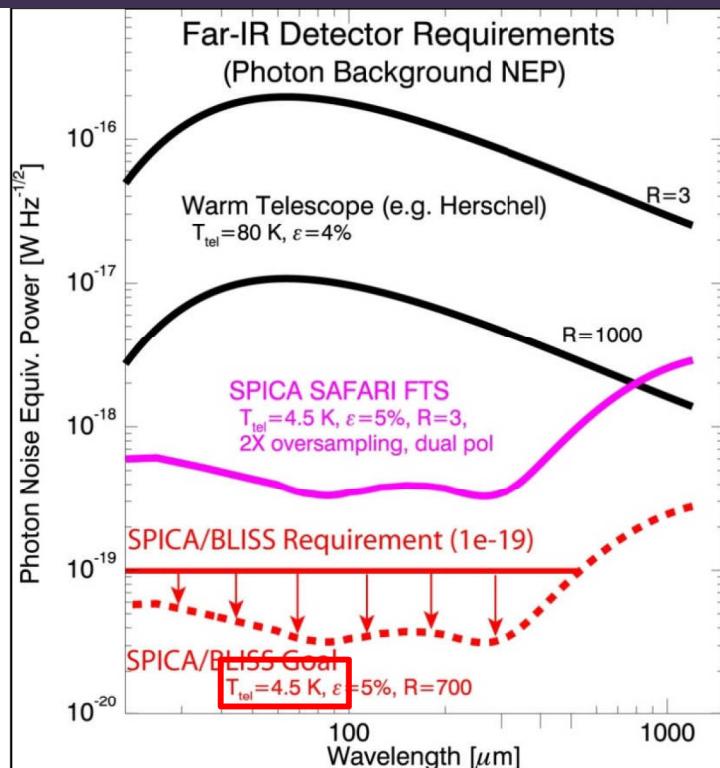
-Zodiacal light, galactic cirrus,  
CMB, telescope, baffles.

Design loading with safety  
factor.

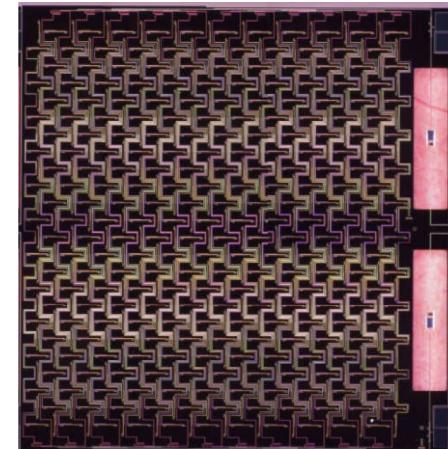
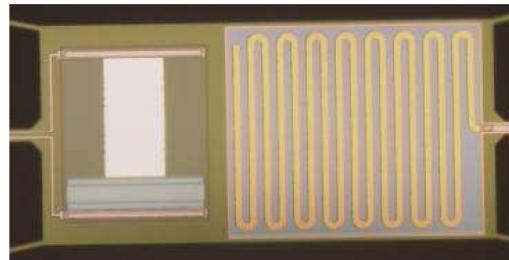
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# BLISS Detector Goals



Dual TESs: Successful in our CMB-pol arrays.



Absorbers are large so heat capacity must be small.

Thermal conductance G is very small.

## Parameters & requirements:

Band	λ <sub>center</sub> (μm)	Pixel Δx (μm)	Pixel Δy (μm)	Q (aW)	NEP ( $\times 10^{-20} \text{ W/Hz}^{1/2}$ )	G (fW/K)	τ (ms)	Dynamic range
					Phonon Detector Margin			Mo/Au Ti
1	53	306	193	0.12	3.1	2.8	5	400 15000
2	92	535	337	0.13	2.4	2.8	5	400 15000
3	148	873	140	0.25	2.6	2.8	5	200 8000
4	230	1353	216	0.34	2.4	2.8	5	150 6000
5	357	2097	336	2.29	5	5	5	75 3000

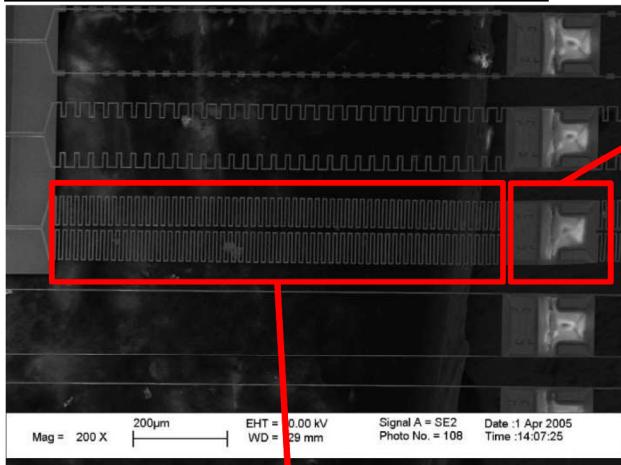
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# Measuring thermal conductance: TESs

Micrograph of long beam TES:



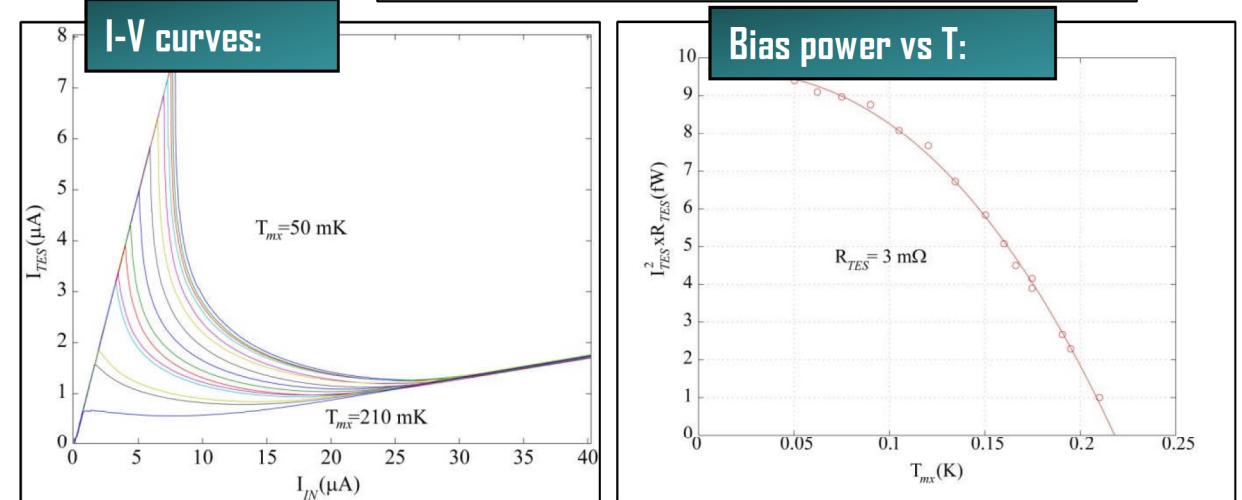
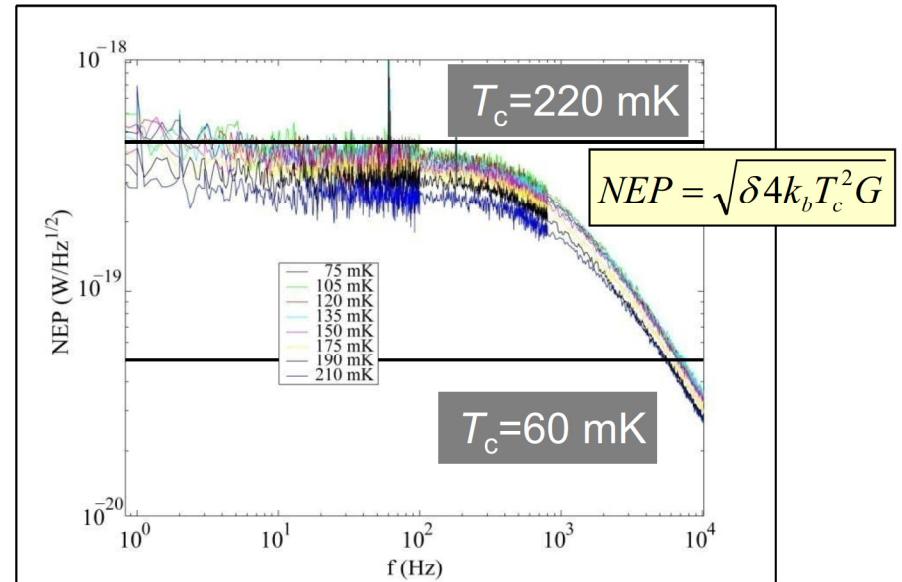
8.3mm long SiN support beams

Extrapolated NEP:

$T_c$ (mK)	$G$ (fW/K)	NEP (W/Hz $^{1/2}$ )
220	94	$5 \times 10^{-19}$
60	14	$5 \times 10^{-20}!$

SiN with  
Mo/Au thermo.

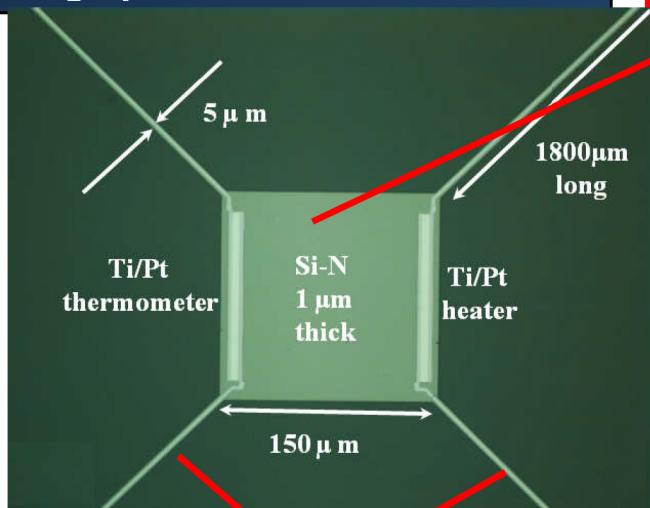
Measurements of TES:





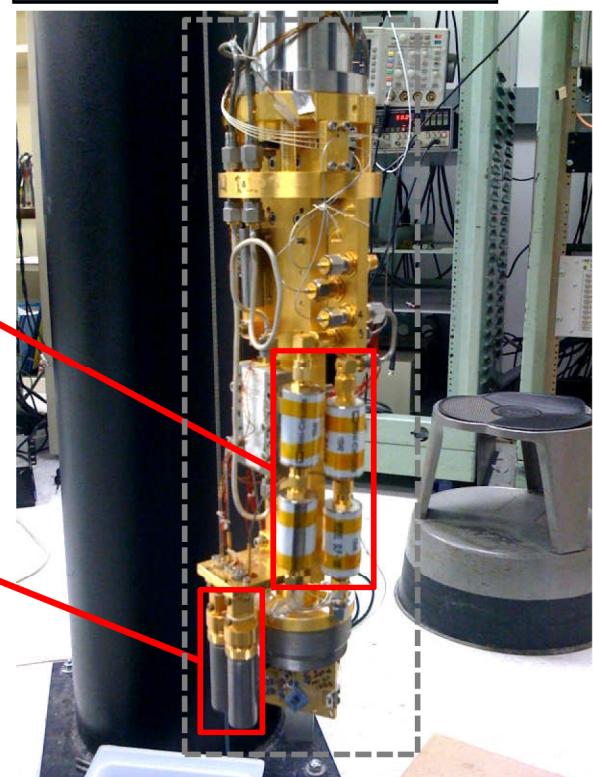
# Measuring thermal conductance: JTDs

Micrograph of noise thermo. device:

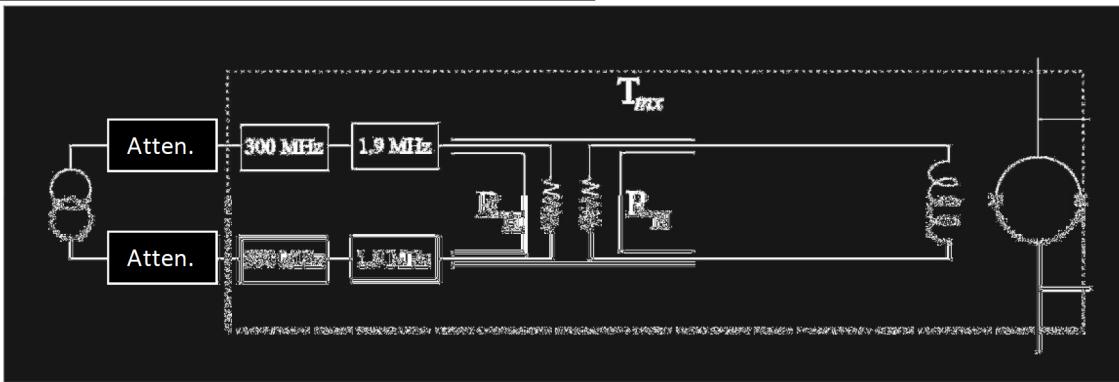


SiN absorber with  $R_H$  &  $R_N$

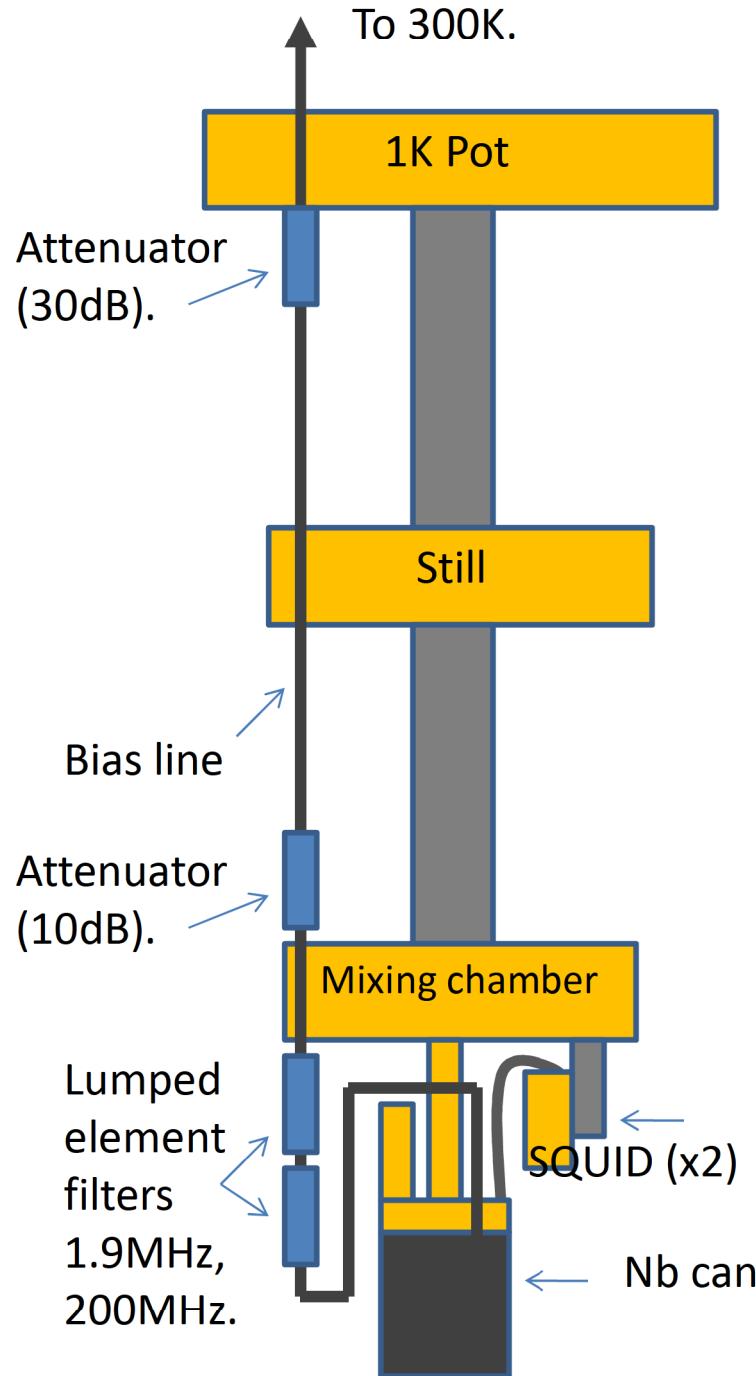
Janis dilution refrigerator:



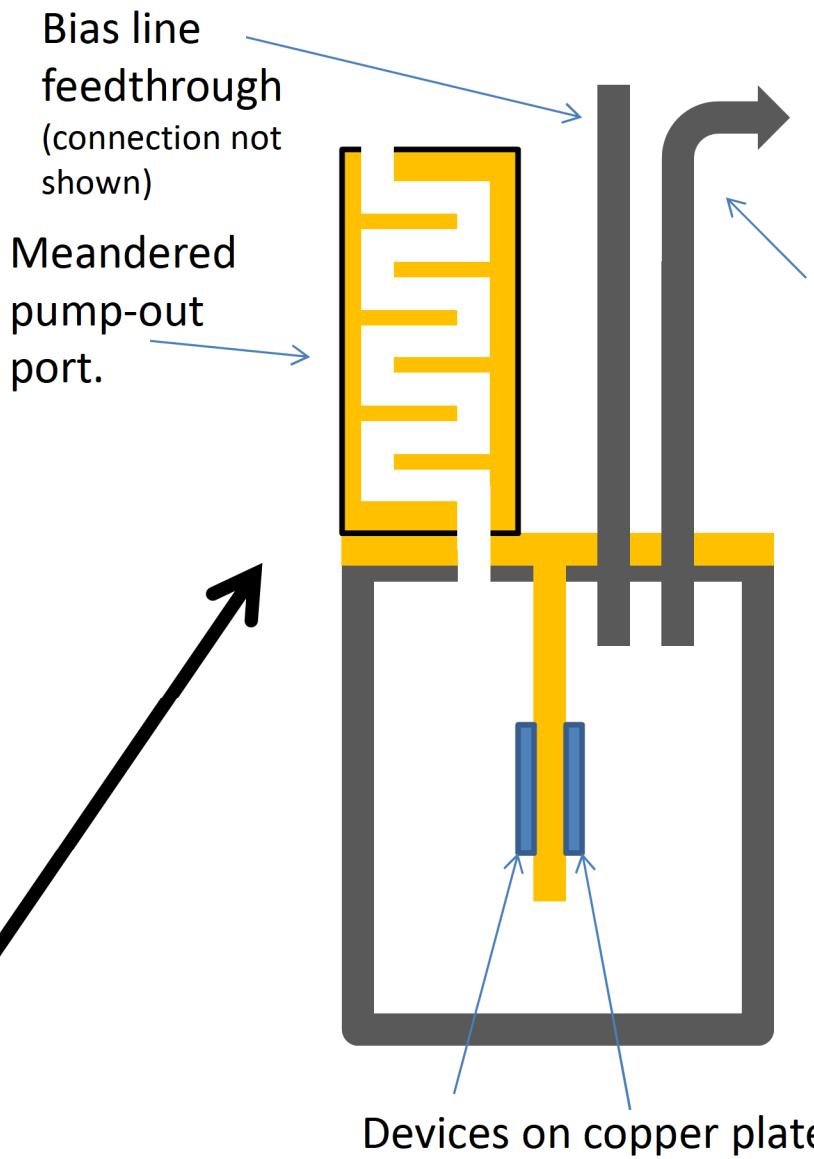
Experimental set-up to measure G:



- Apply power:  $P=I^2 R_H$
- Measure temp:  $4k_b T / R_N$
- Thermal conduct.:  $G=dP/dT$

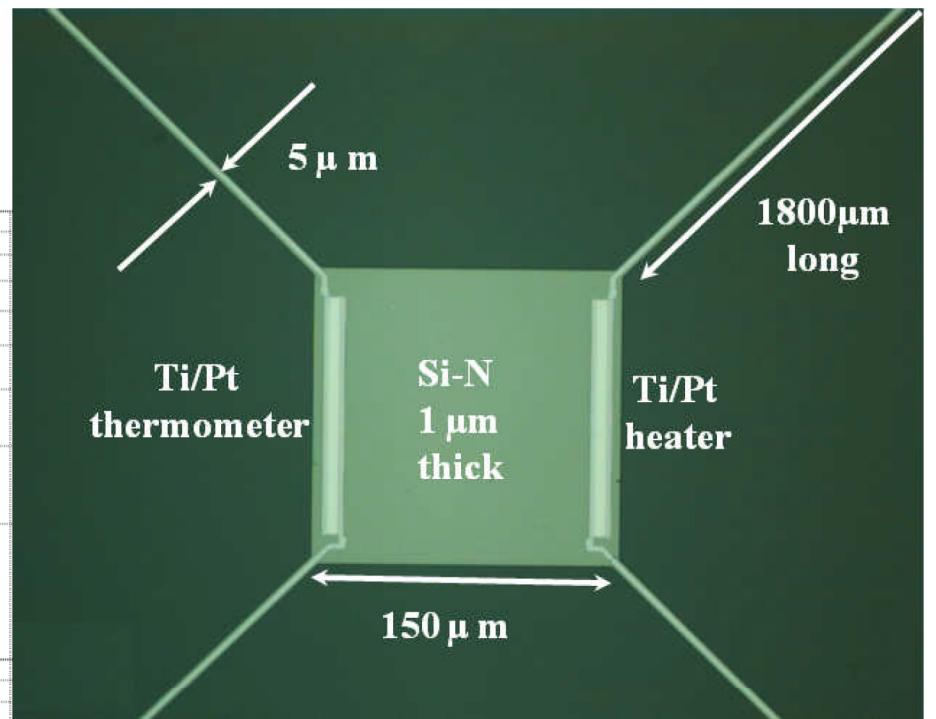
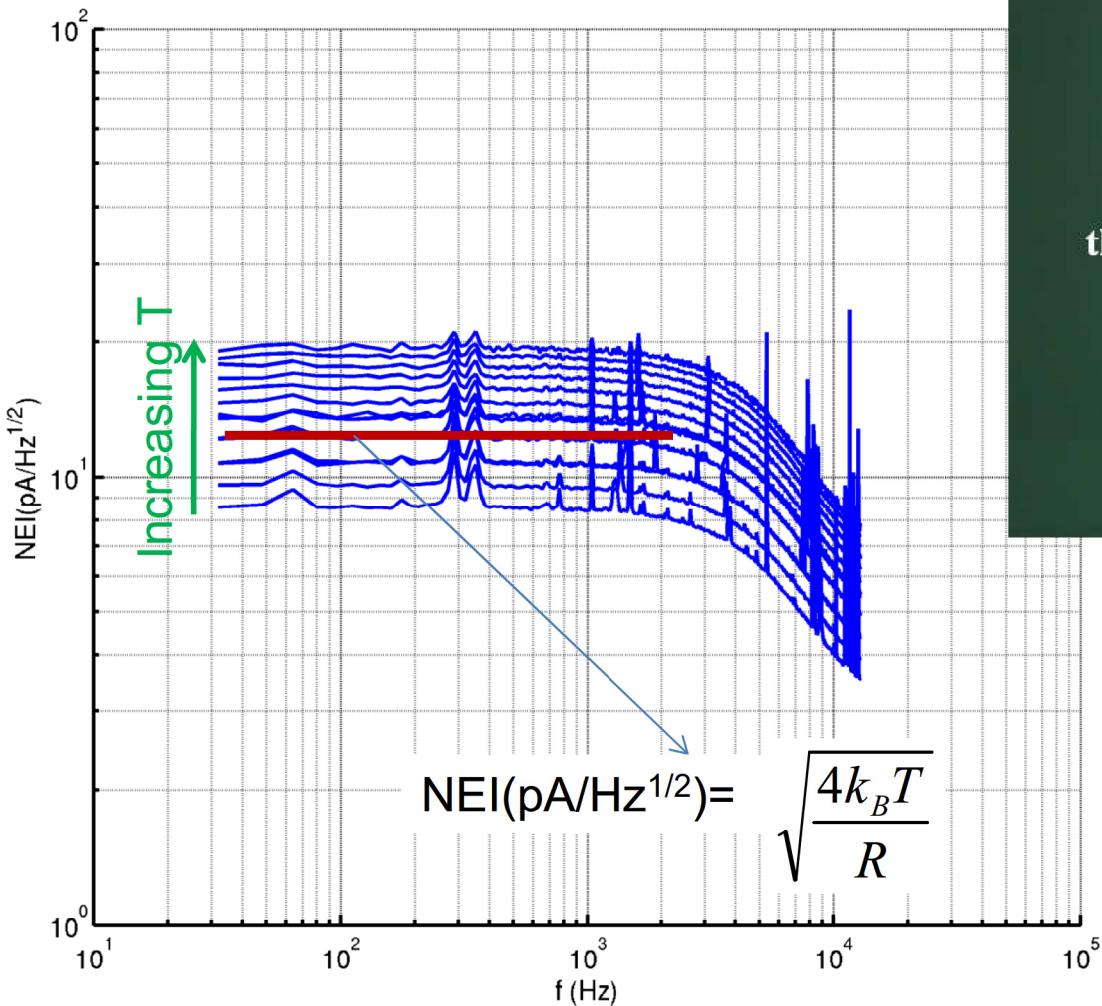


### Nb can (enlarged for detail):





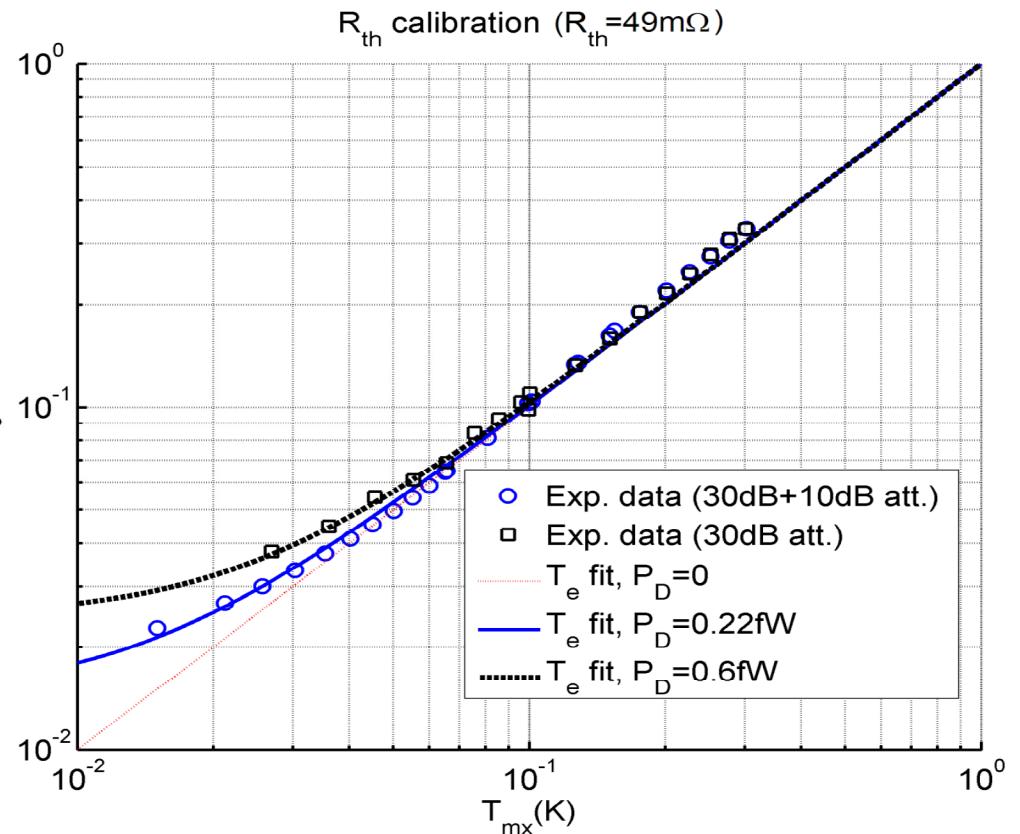
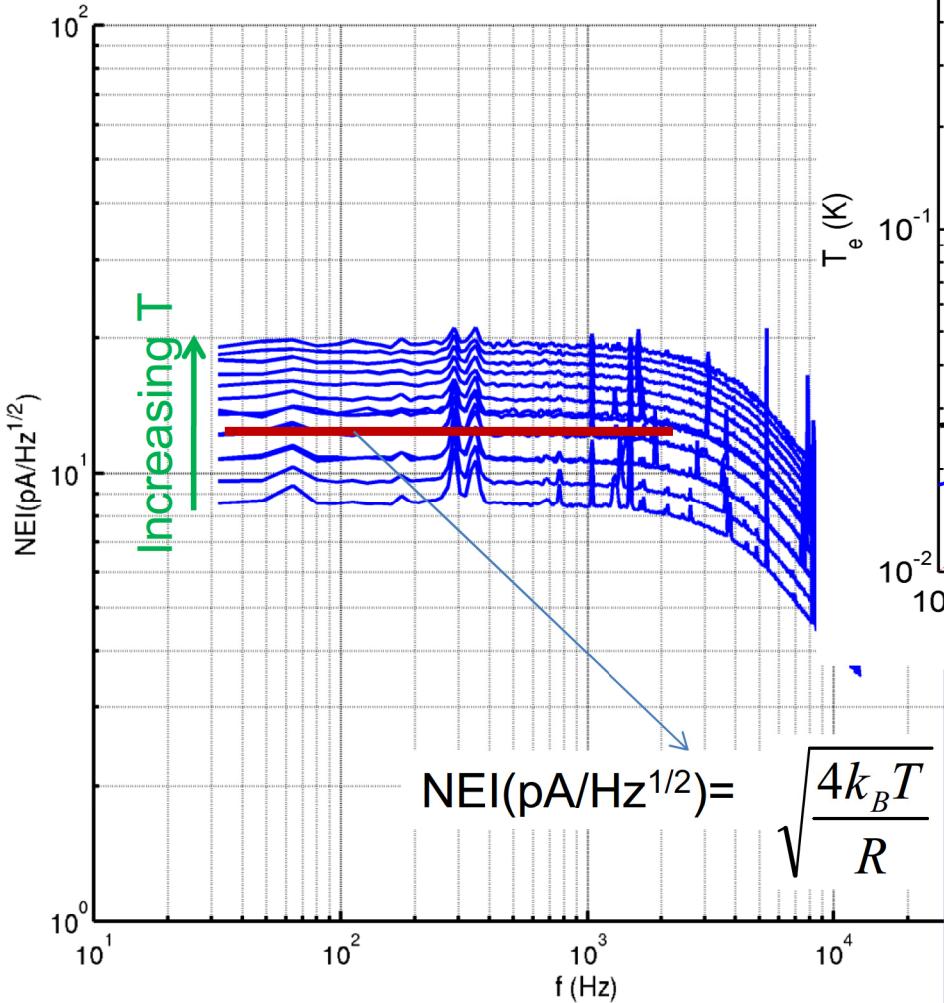
# Experimental setup: how small is G?



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- Measure temp:  $4k_b T/R_N$
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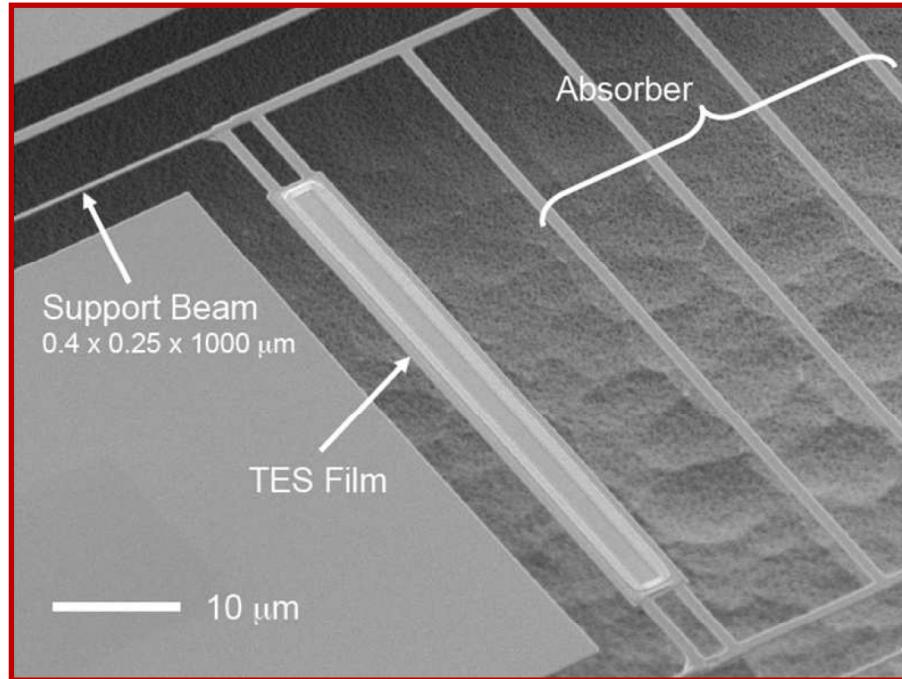


# Experimental setup: how small is G?



$T_e$ —electron temperature on device.  
 $T_{\text{mx}}$ —mixing chamber temperature.

## Dark power



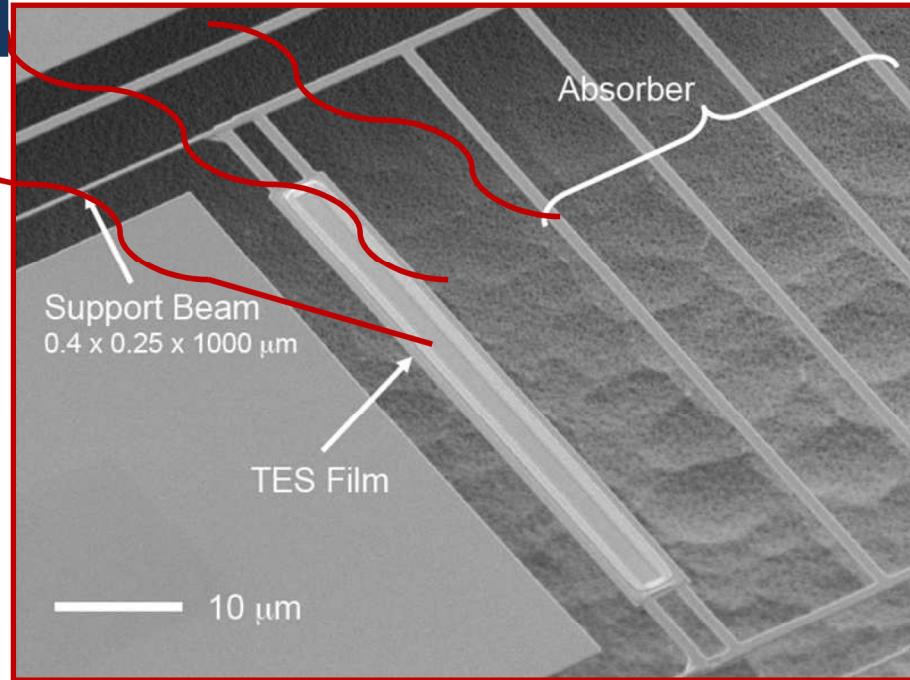
- Electrical dark power (resistors)

$$P_{\text{dark}}/\Delta v = (4k_B T R)^{1/2} \times (4k_B T / R)^{1/2} = 4k_B T.$$

- Electrical dark power: SQUID back-action.
- Stray optical power:

$$N_{\text{dark power}} = (2hvP_{\text{opt}} + P_{\text{opt}}^2 / 2\Delta v)^{1/2}.$$

## Dark power



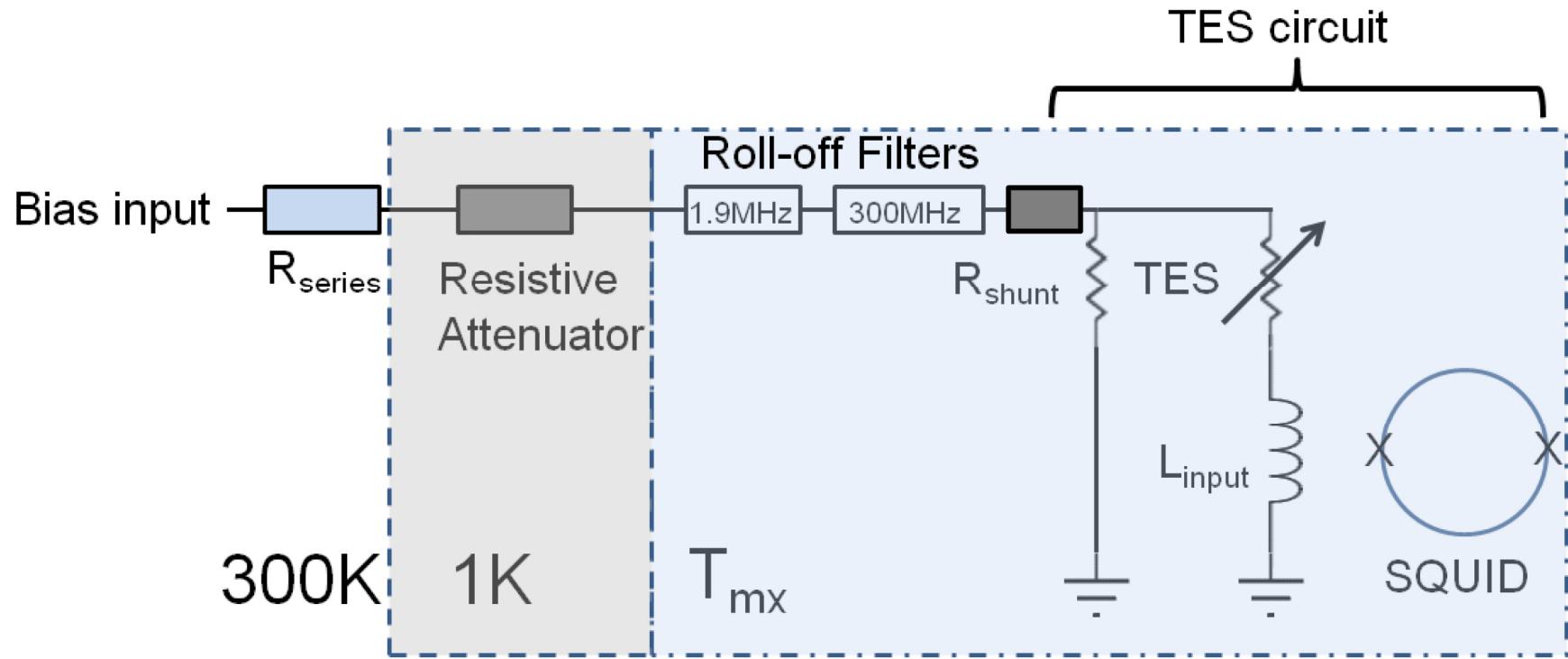
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# Experimental issue: dark power



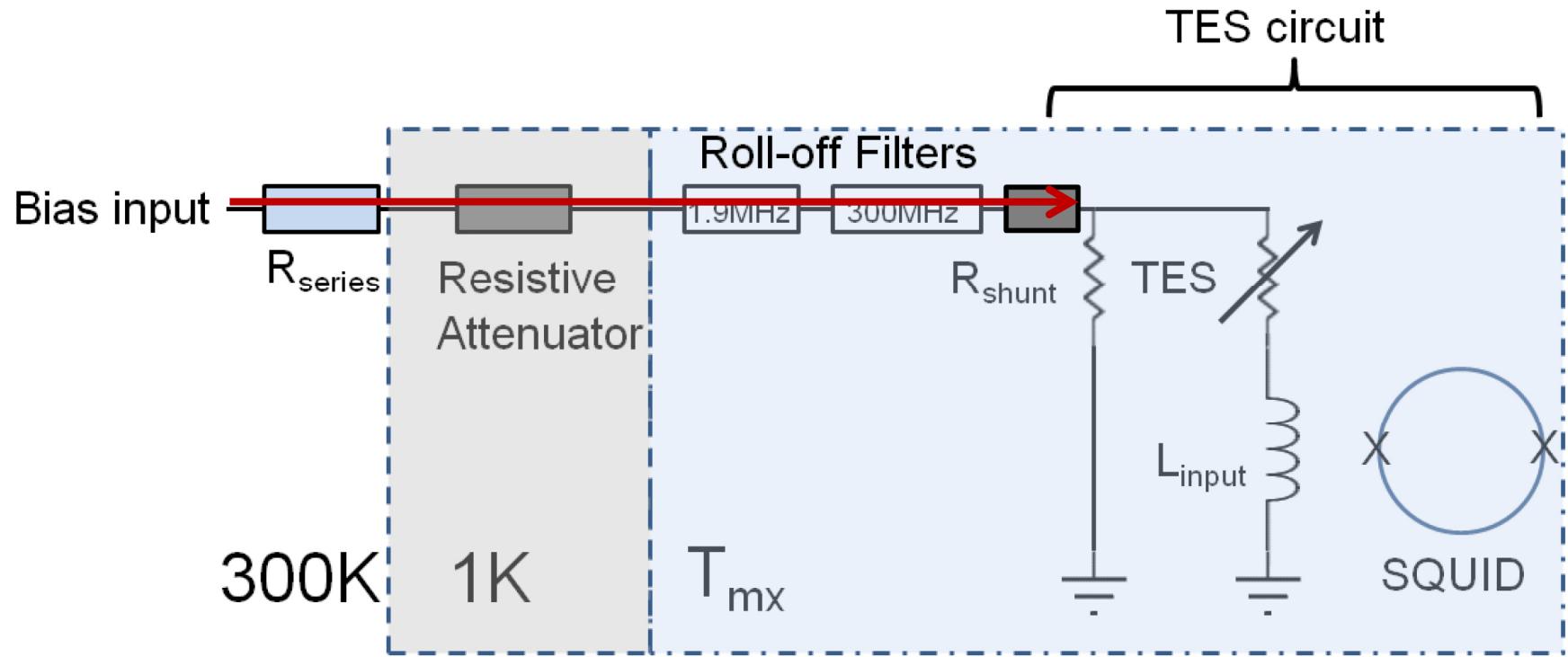
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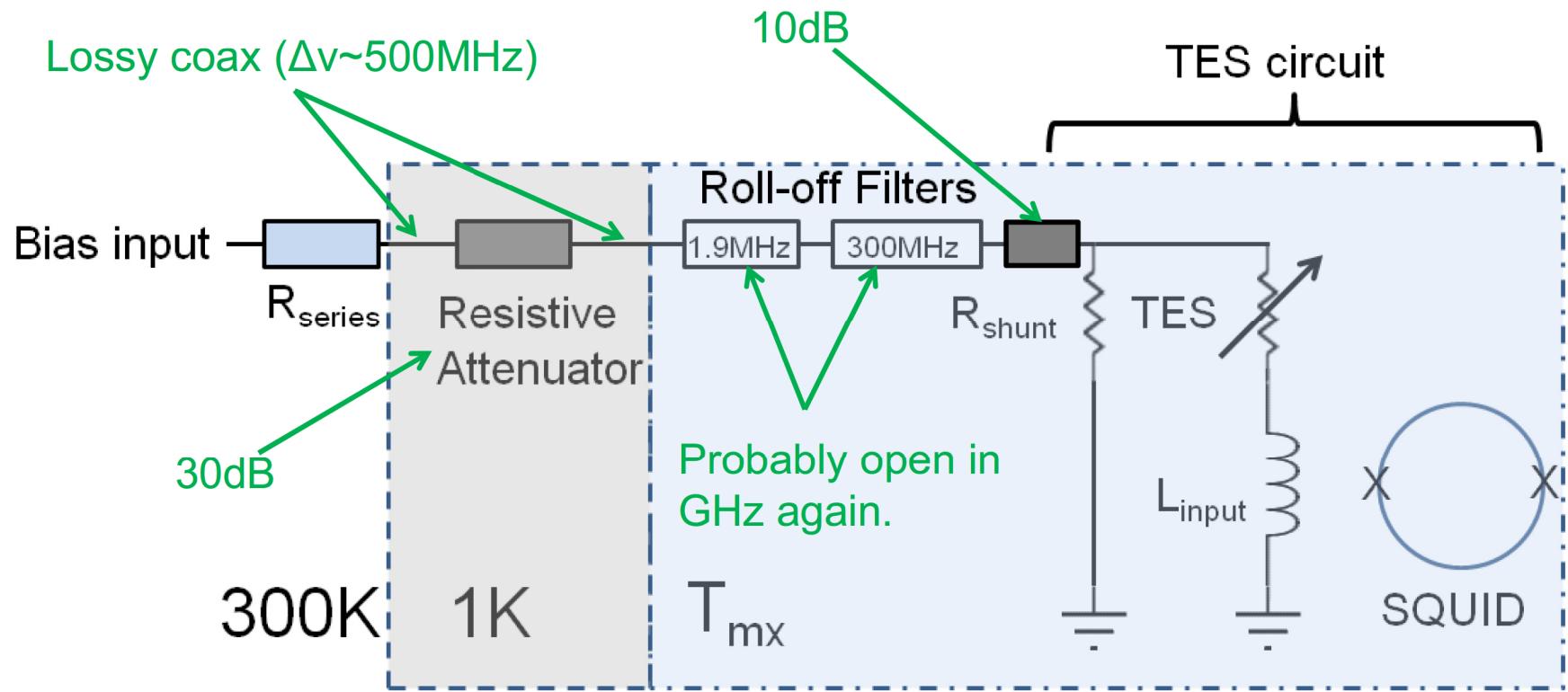
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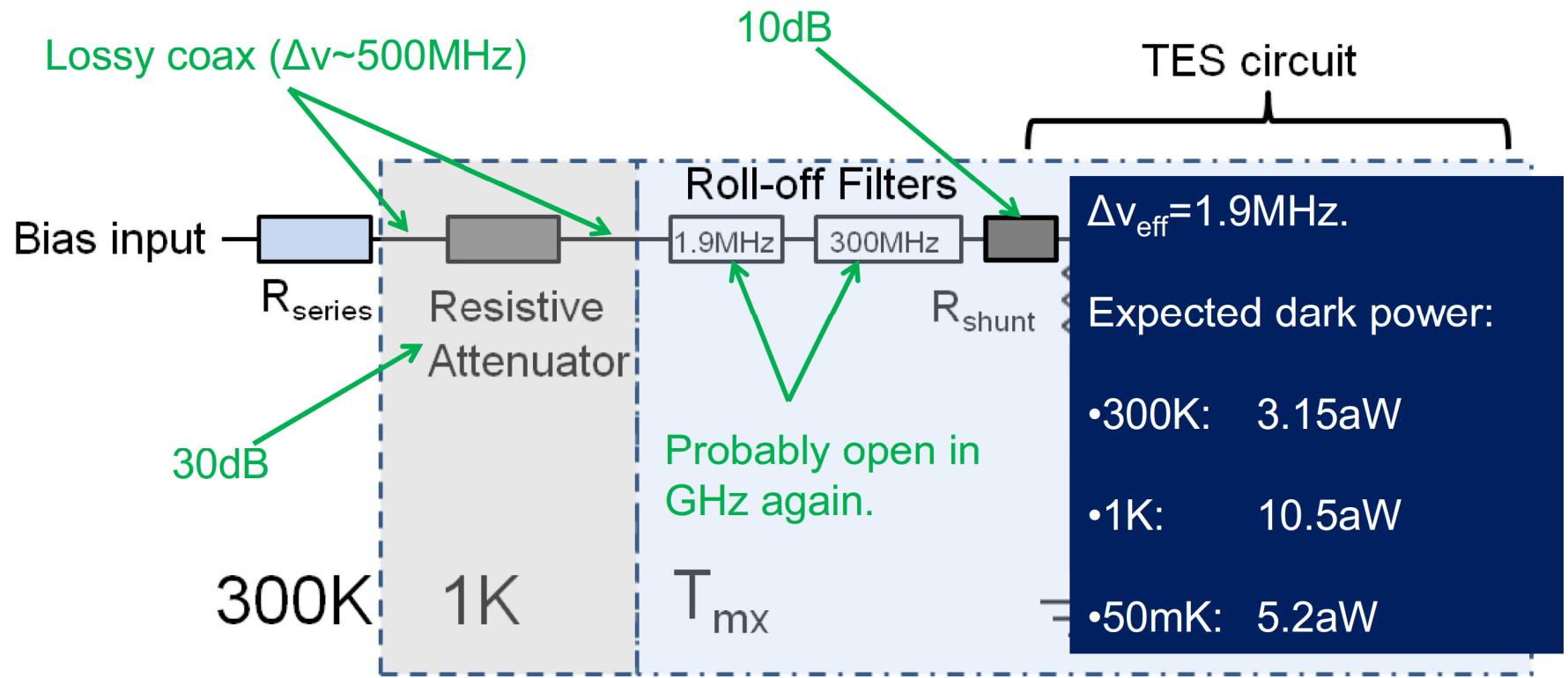
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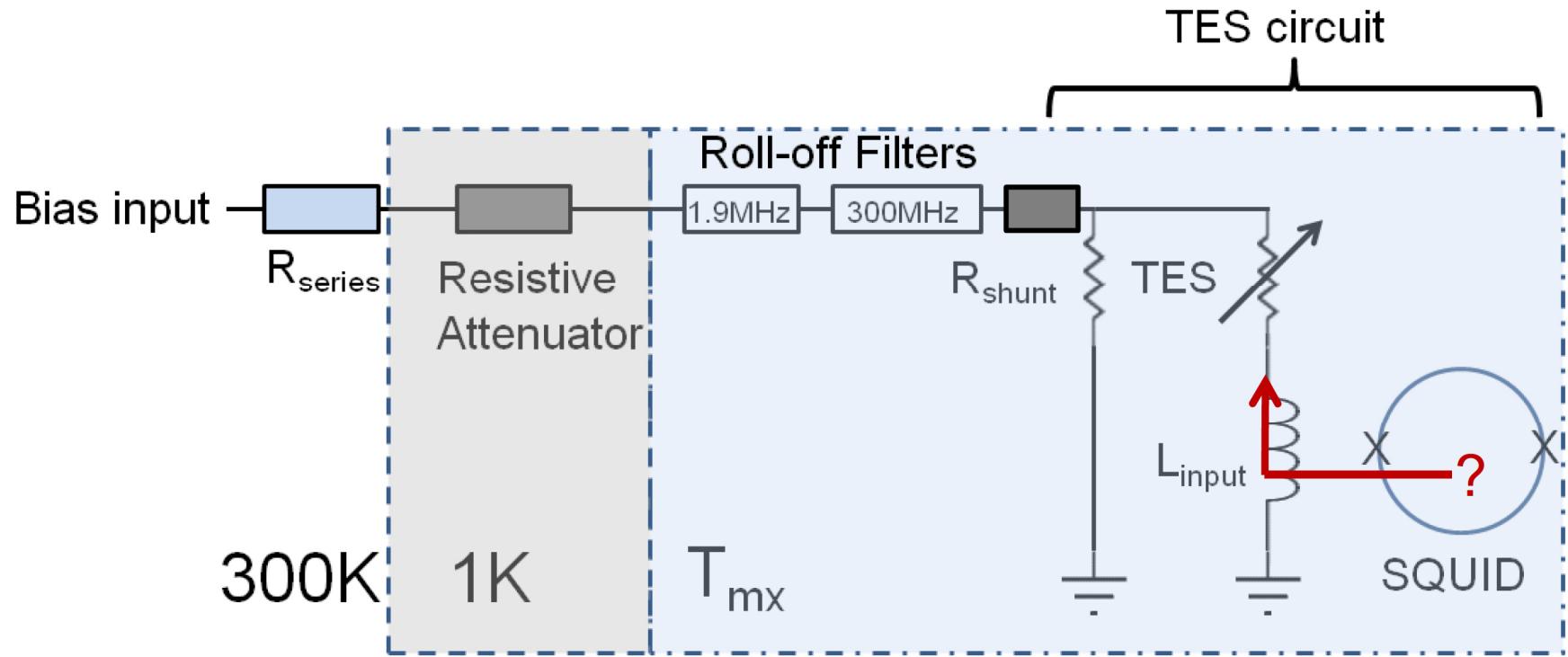
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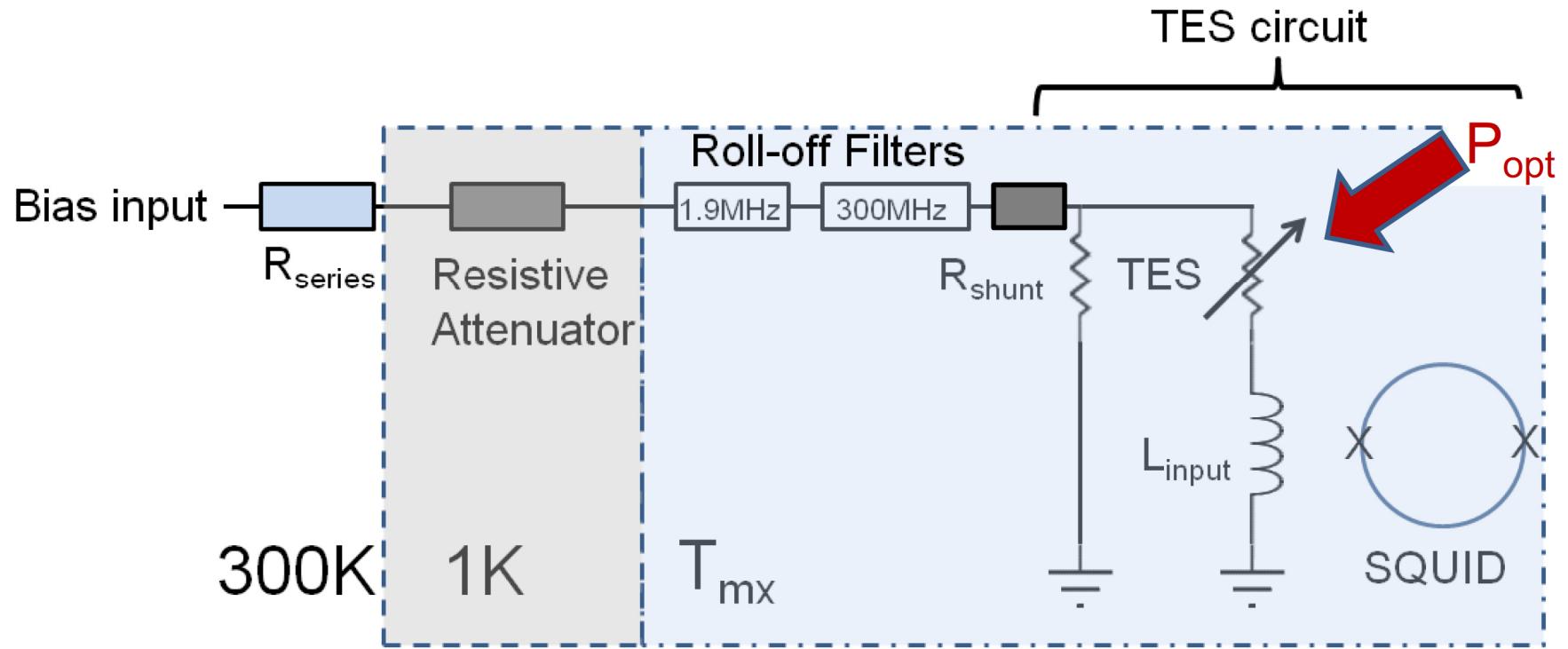
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- Electrical dark power: SQUID back-action.

- Stray optical power:

$$N_{\text{dark power}} = (2hvP_{\text{opt}} + P_{\text{opt}}^2 / 2\Delta v)^{1/2}.$$

# Experimental issue: dark power



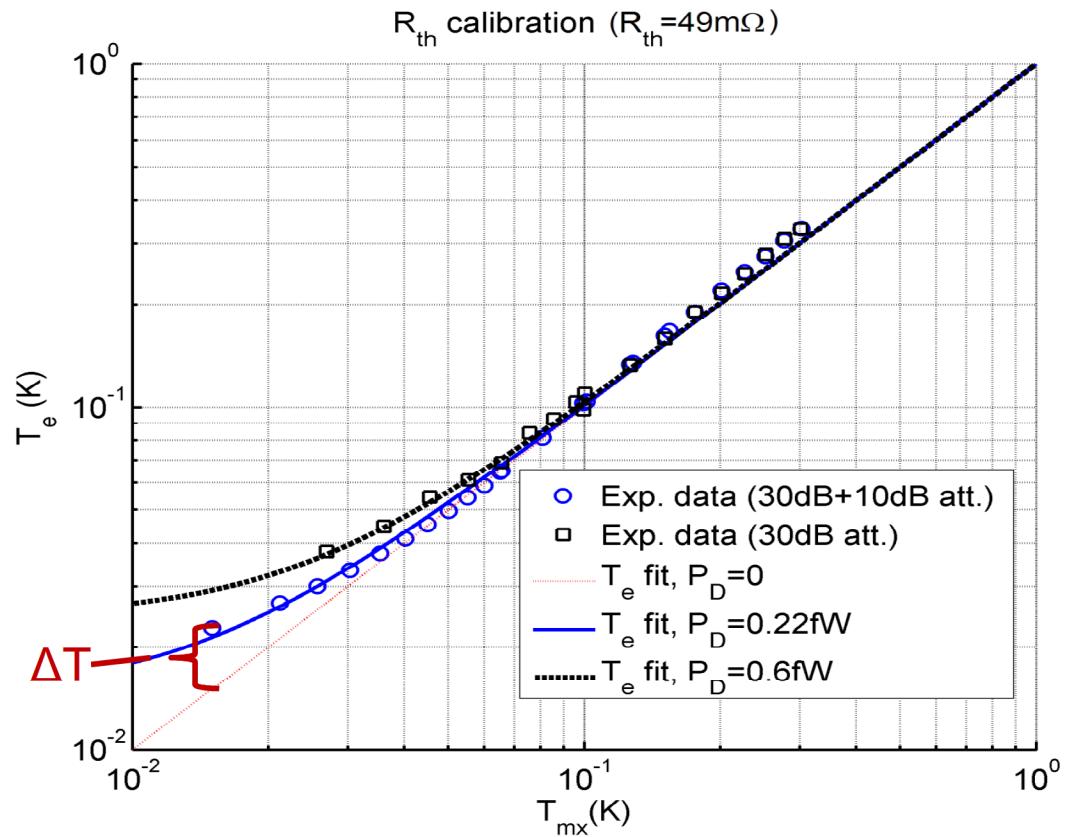
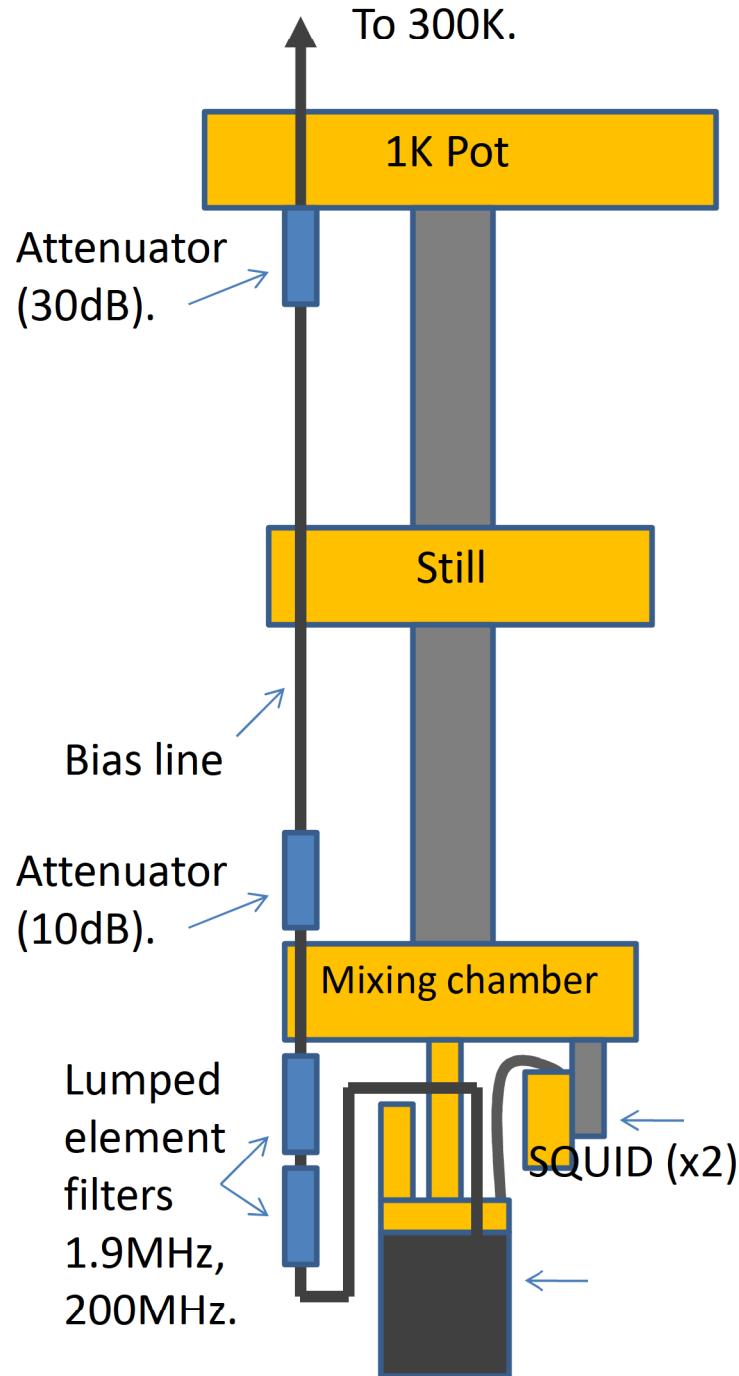
- Electrical dark power (resistors)

$$P_{\text{dark}}/\Delta v = (4k_B T R)^{1/2} \times (4k_B T / R)^{1/2} = 4k_B T.$$

- Electrical dark power: SQUID back-action.

- Stray optical power:

$$N_{\text{dark power}} = (2hvP_{\text{opt}} + P_{\text{opt}}^2 / 2\Delta v)^{1/2}.$$



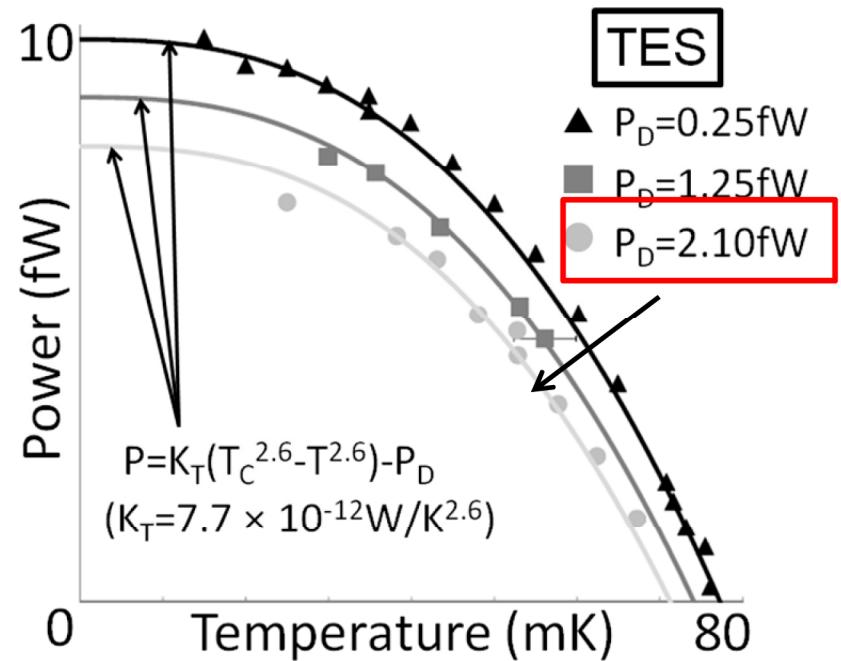
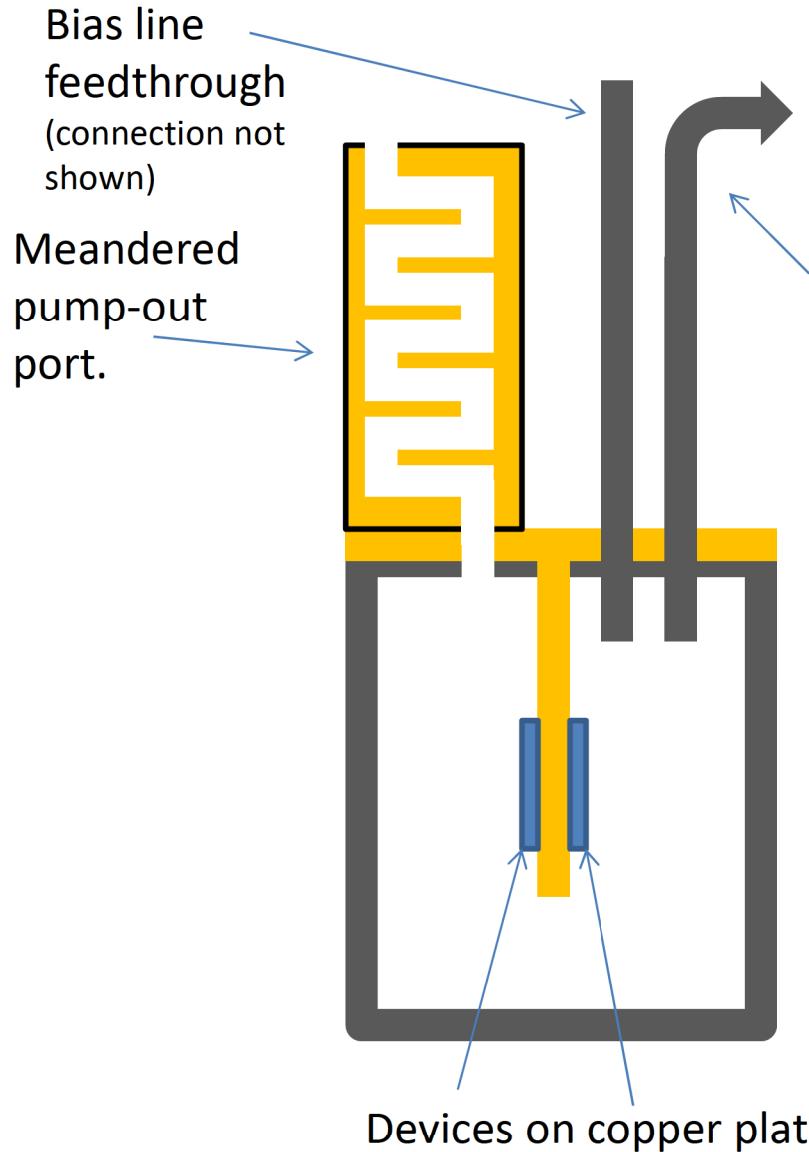
$$T_e = T_{mx} + \Delta T ; \quad [NEI = (4k_B T_e / R)^{1/2}] .$$

$$\Delta T = P_D / G(T) .$$

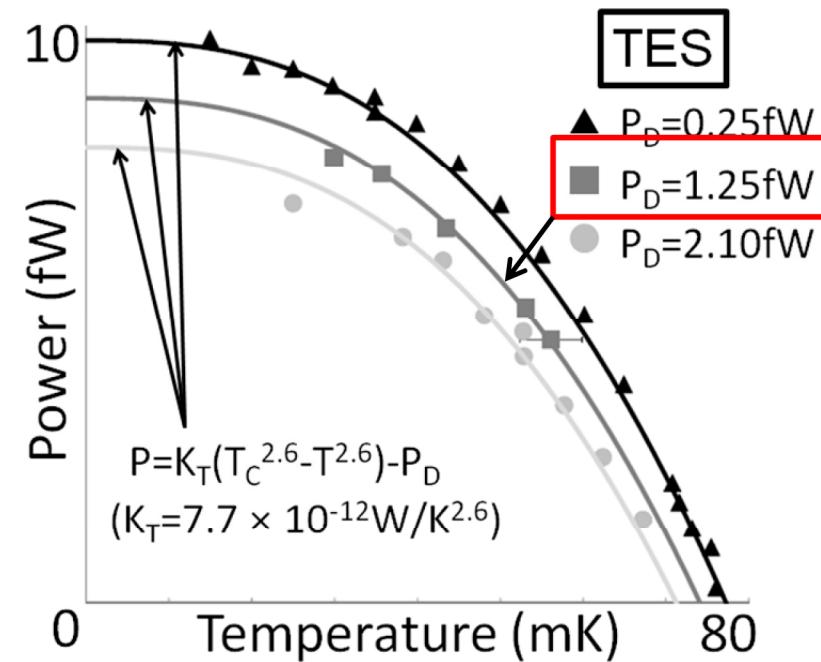
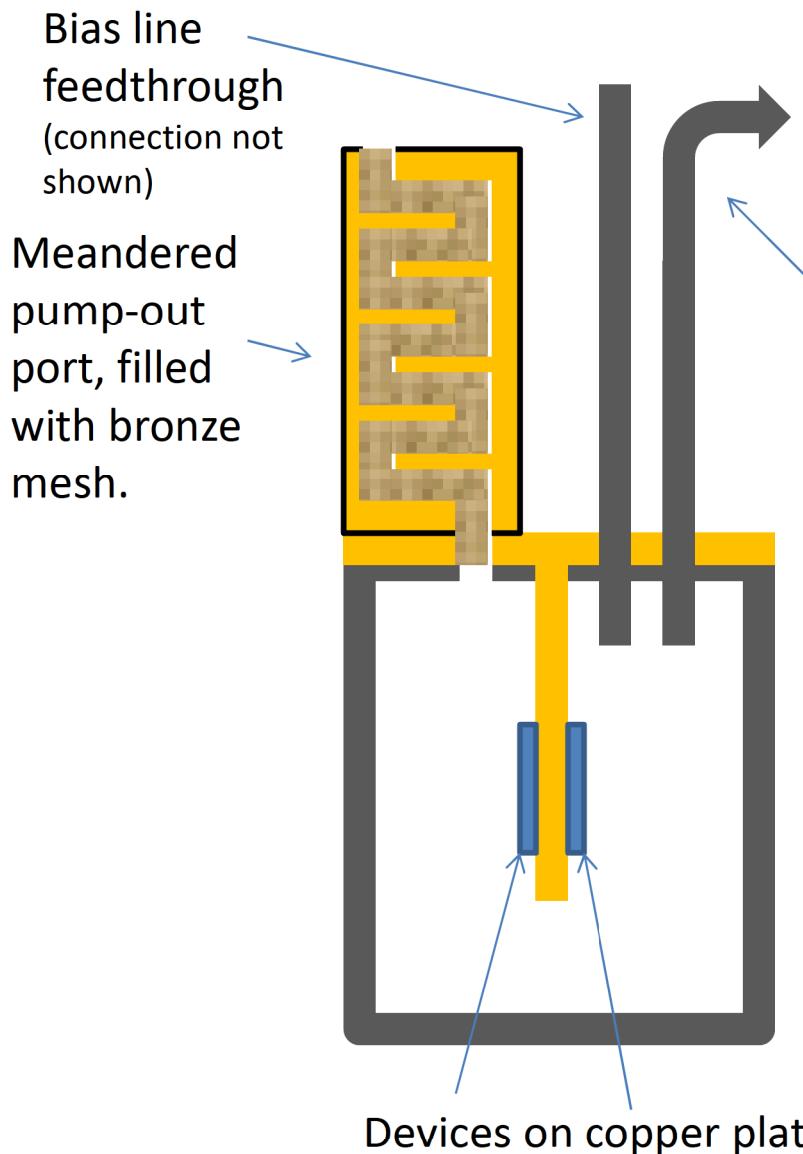
$T_e$  — electron temperature on device.

$T_{mx}$  — mixing chamber temperature.

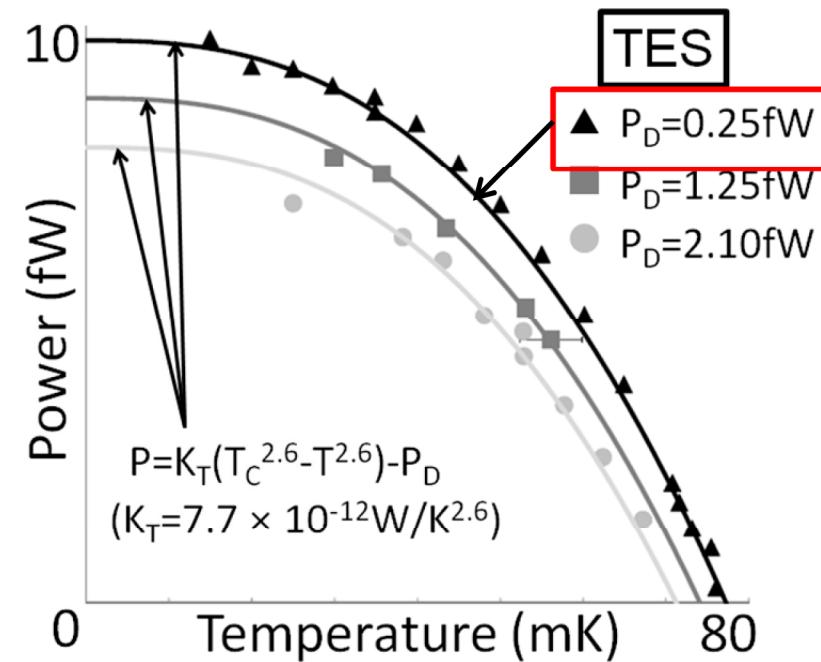
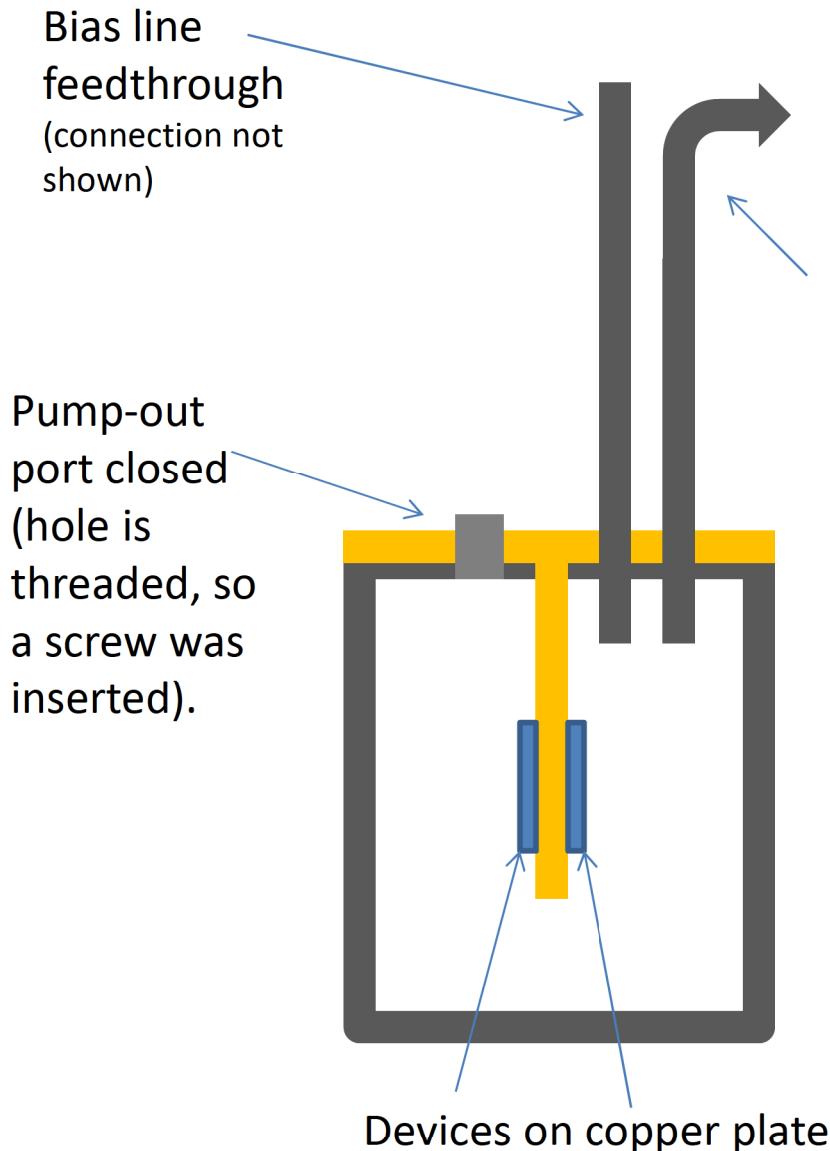
## Nb can (enlarged for detail):



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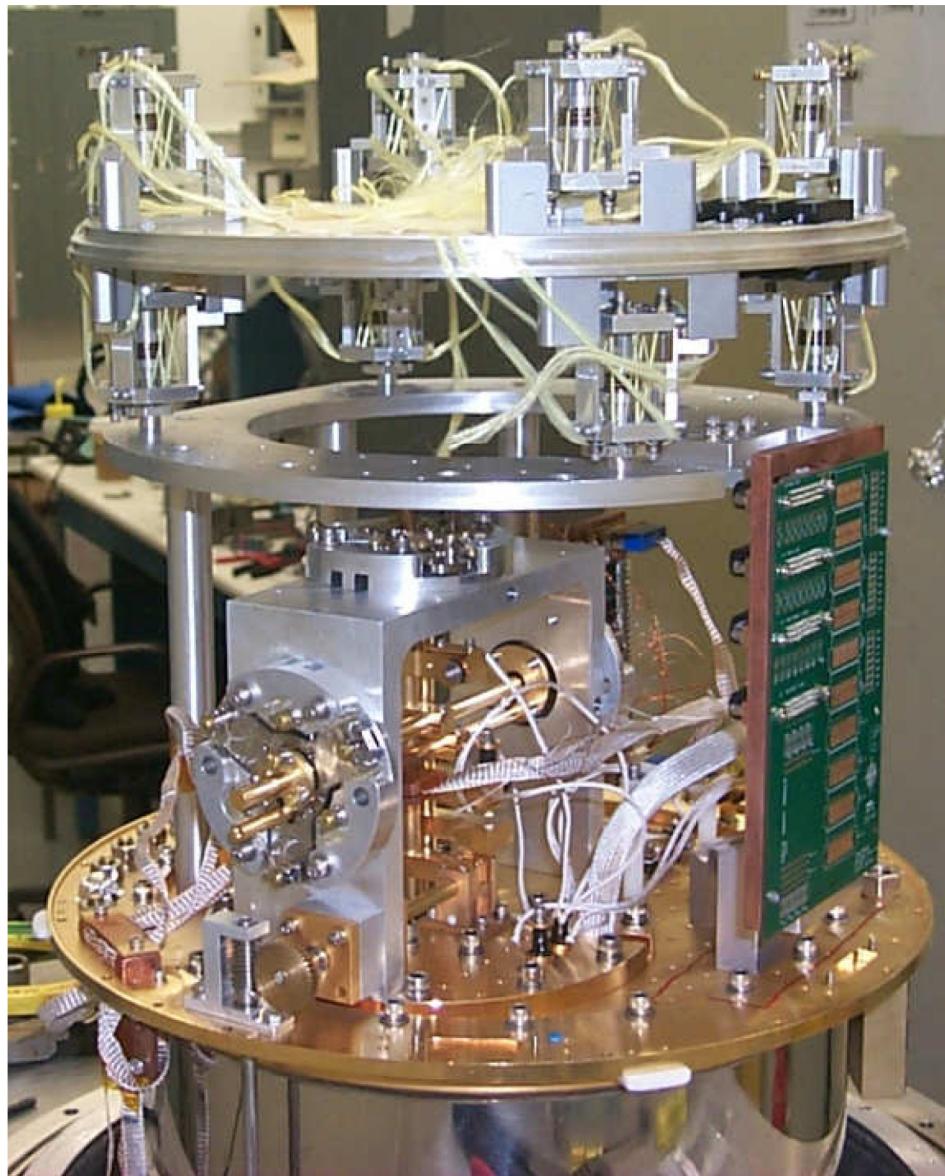
Important:

- JTD and TES measured simultaneously ( $P_D$  known).
- **Tc must be known for TES alone.**

# Outline

1. Motivation and intro to TESs.
2. BLISS Specifications—tolerance to dark power
3. Measuring stray (dark) power— $T_c$  (alpha) and G measurements
  - a. Overview two methods: JTD vs. TES
  - b. TES arrays: measurement complications for  $P_d$ ,  $T_c$ , and alpha.
4. Results:  $P_d$  compare, NEP, tau, 1/f issues

# Testing arrays of BLISS TESs



## Array testbed

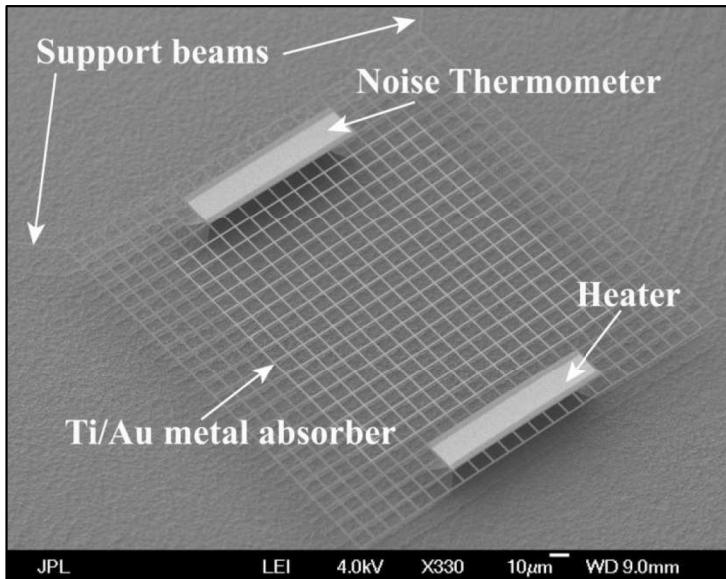
Adiabatic demagnetization refrigerator (ADR) testbed:

- Up to  $8 \times 32$  channels. Can reach 40mK.

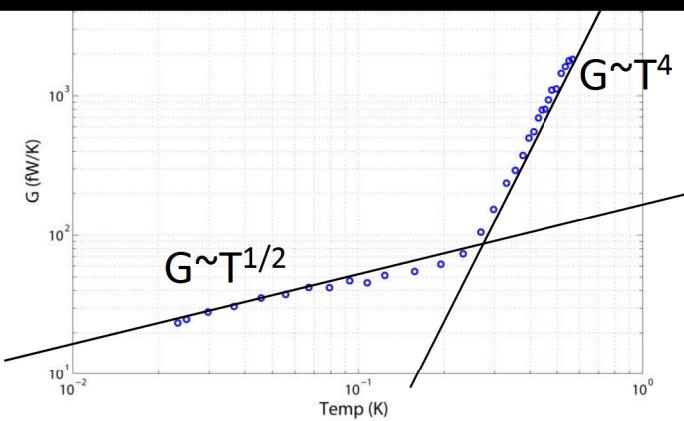
# G, C for BLISS-like NTDs



**Micrograph noise thermo. device:**



**Thermal conductance vs. Fridge temp**



**Device parameters:**

**SiN:** 14625  $\mu\text{m}^2$  area. 0.250  $\mu\text{m}$  thick. 20nm  $\text{SiO}_2$  layer underneath SiN.

**Support beams:** 4 x 0.4  $\mu\text{m}$  wide x 1000  $\mu\text{m}$  long.

**Au absorber:** 10nm thick, volume=27  $\mu\text{m}^3$ .

**Au heater & thermo:** 50nm thick, volume=194  $\mu\text{m}^3$ .

Device is dry released ( $\text{XeF}_2$ ).

**Measurement results:**

Device	C (fJ/K)	G (fW/K)	$\text{Si}_x \text{N}_y$ ( $\mu\text{m}$ )	N	NEP (W/Hz $^{1/2}$ )
1	-	25	0.25	0.5	$7 \times 10^{-20}$
2	85	40	0.125	0.5	$8 \times 10^{-20}$
3	130	65	0.25	0.5	$1 \times 10^{-19}$
4	100	65	0.25	1	$1 \times 10^{-19}$
5	90	100	0.25	0.5	$1.5 \times 10^{-19}$
6	80	40	0.25	0.5	$8 \times 10^{-20}$
7	100	40	0.25	0.7	$8 \times 10^{-20}$

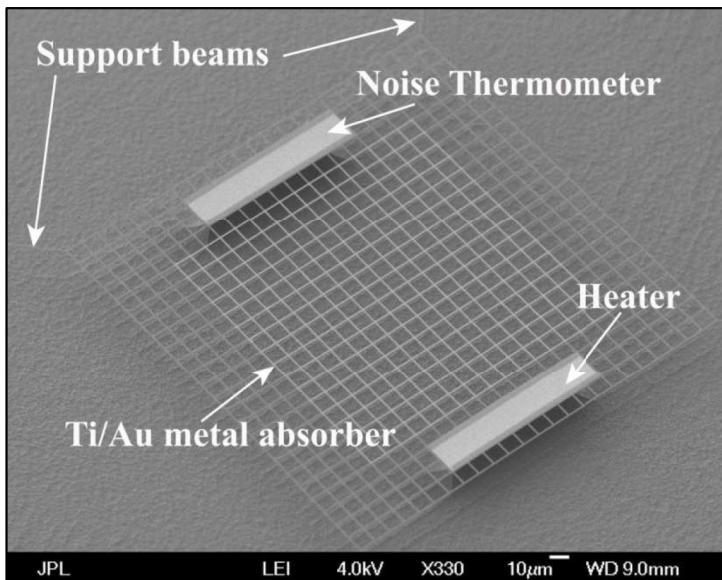
**G, NEP meet BLISS specs**

**C is much larger than expected. TES may be too slow.**

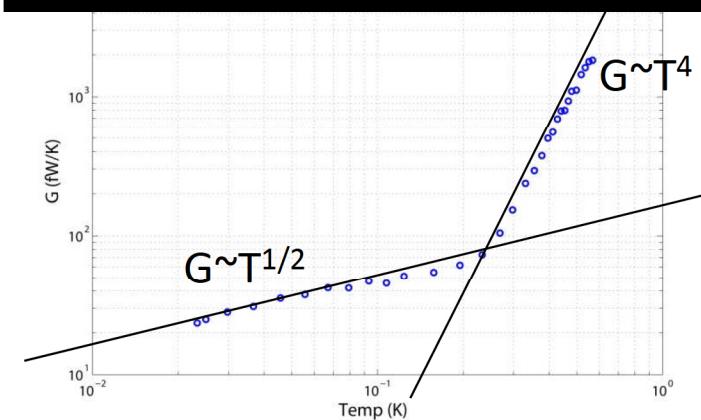
# G, C for BLISS-like NTDs



Micrograph noise thermo. device:



Thermal conductance vs. Fridge temp



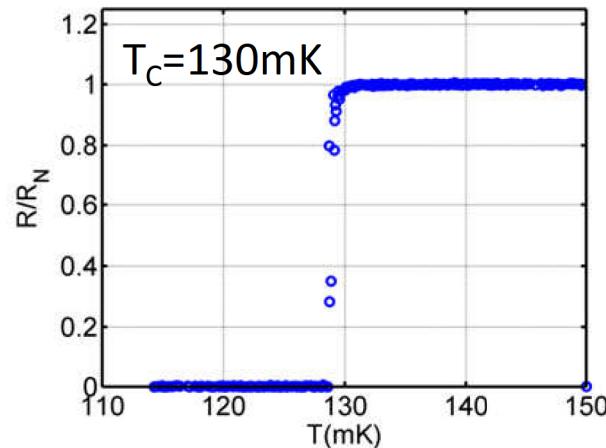
Given a background limited device ( $G=15\text{fW/K}$ ) with  $T_c=65\text{mK}$ , and  $G \sim T^{1/2}$ , we need:

$$P_{\text{dark}} < 200\text{aW} \text{ at } 50\text{mK.}$$

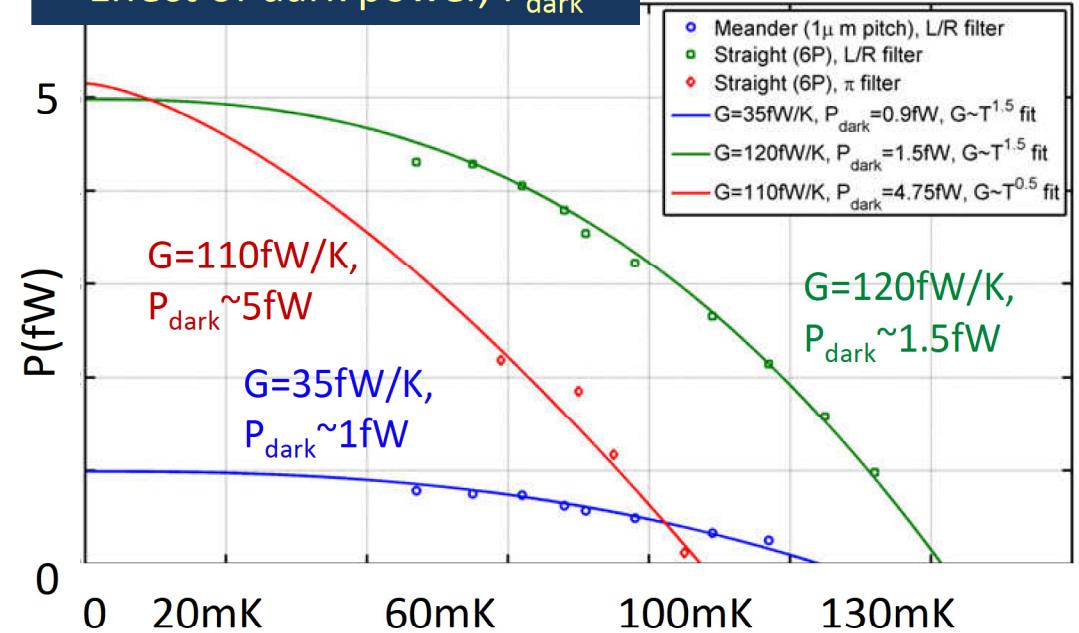


# Mitigating dark power, $P_{\text{dark}}$

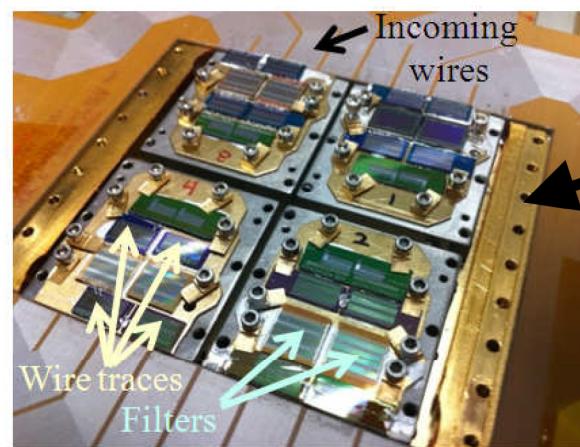
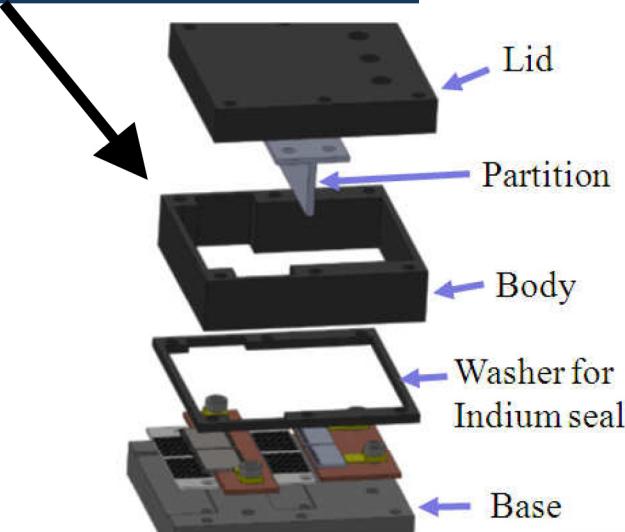
Actual  $T_c$



Effect of dark power,  $P_{\text{dark}}$



Light-tight box (optical  $P_{\text{dark}}$ )



Electrical filtering (electrical  $P_{\text{dark}}$ )

# G, C for BLISS-like NTDs



Given a background limited device ( $G=15\text{fW/K}$ ) with  $T_c=65\text{mK}$ , and  $G \sim T^{1/2}$ , we need:

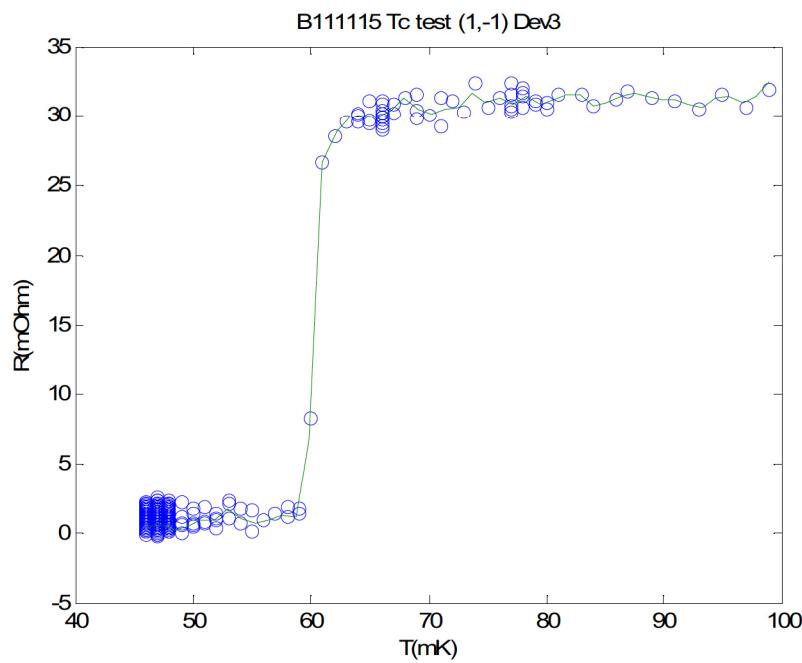
$$P_{\text{dark}} < 200\text{aW at } 50\text{mK.}$$

- To gauge  $P_d$  correctly, you must know  $T_c$ !

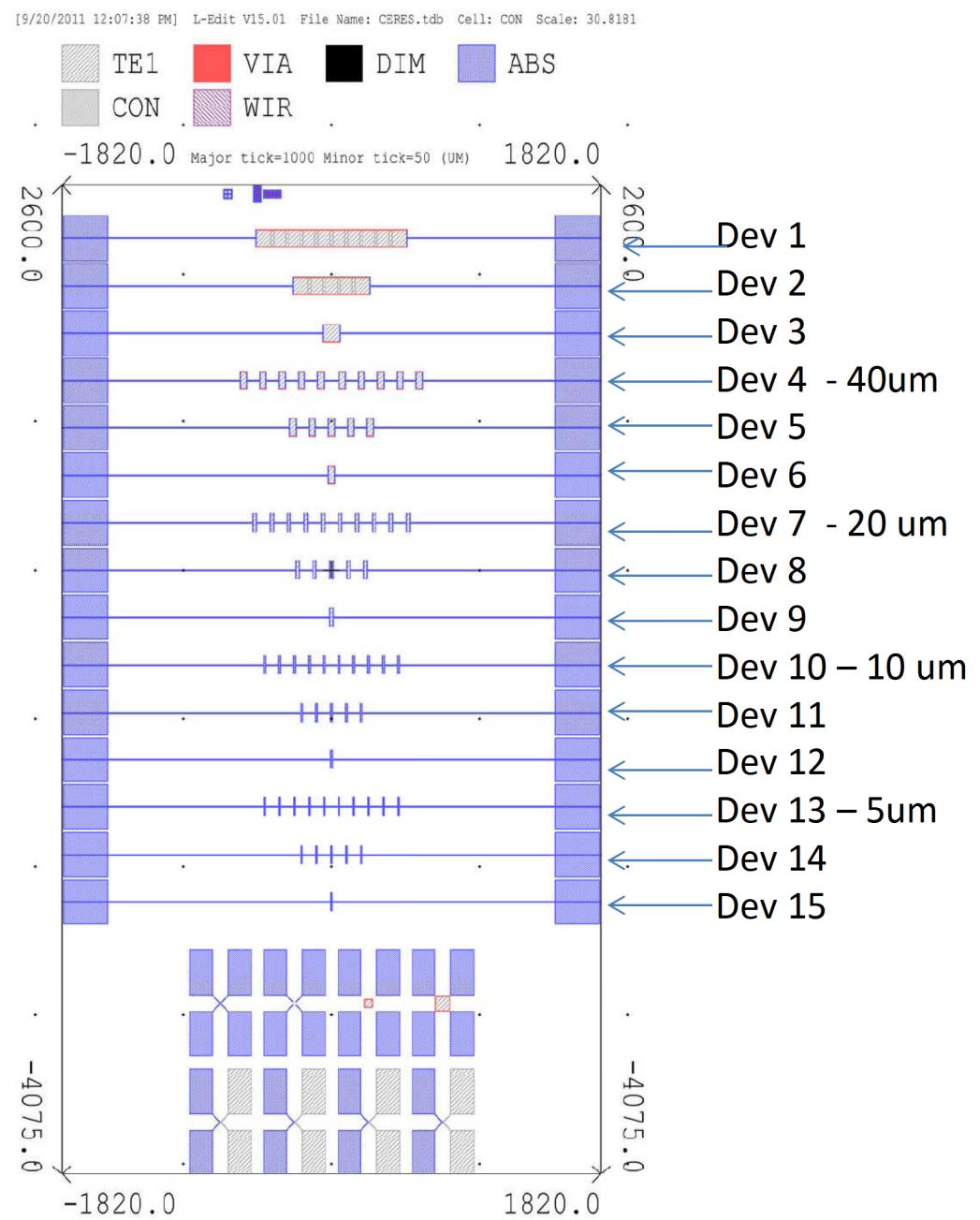
$R/\square = 30\text{m}\Omega$ .

→  $R_n = 3\text{m}\Omega$  at  $10\mu\text{m}$ .

→  $R_n = 10\text{m}\Omega$  at  $33\mu\text{m}$ .



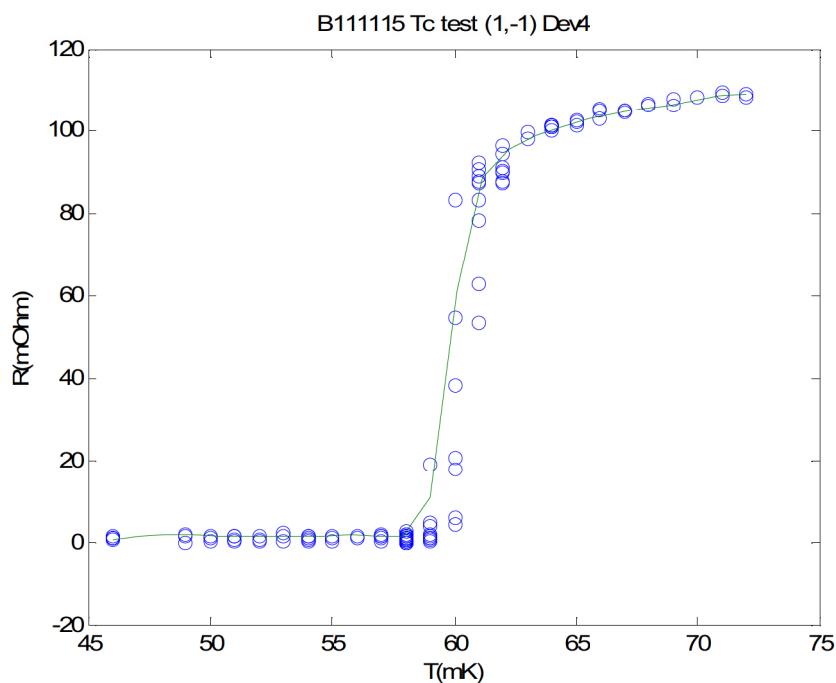
B111115 BLISS Tc test design  
Mo/Cu/Ti recipe  
TiN wire



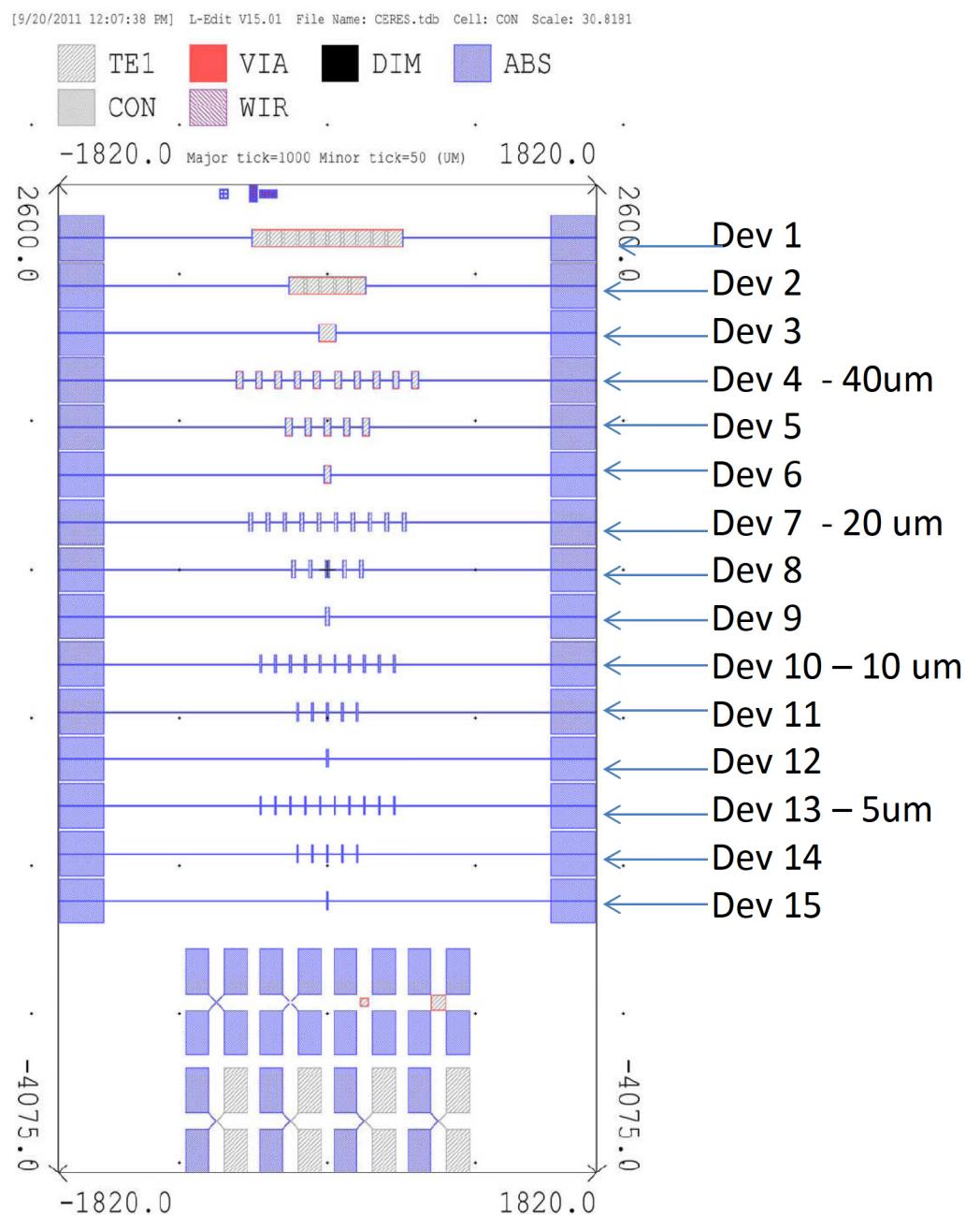
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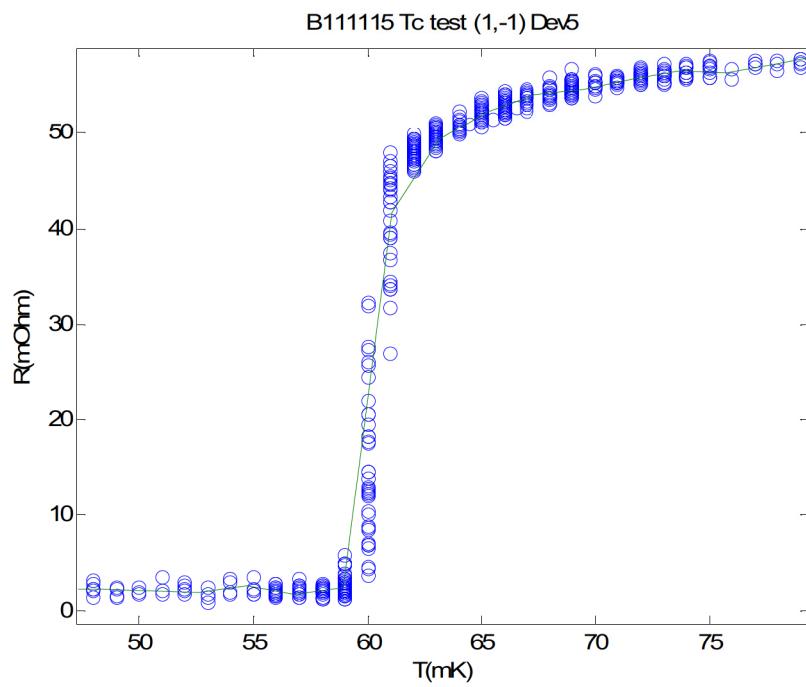
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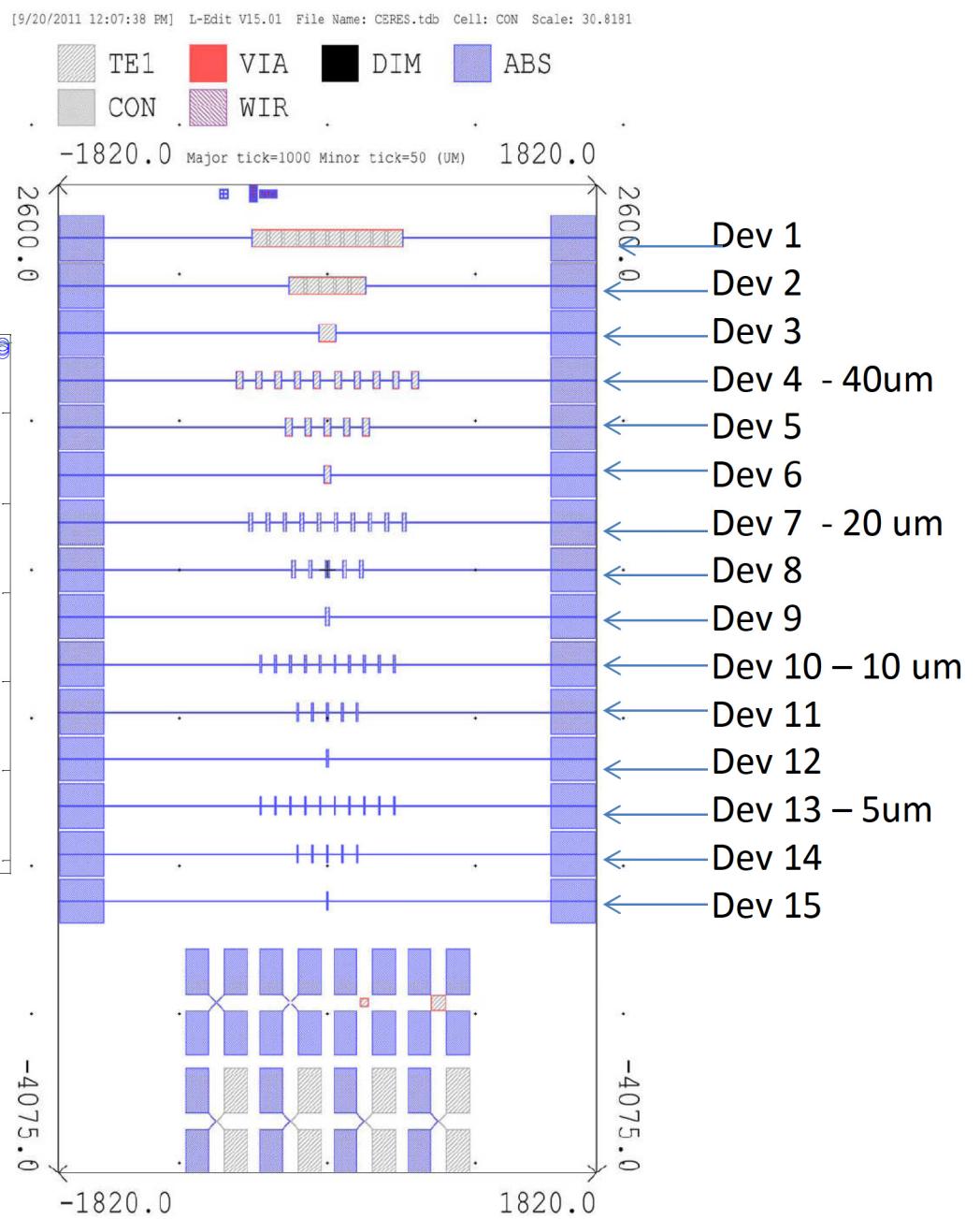
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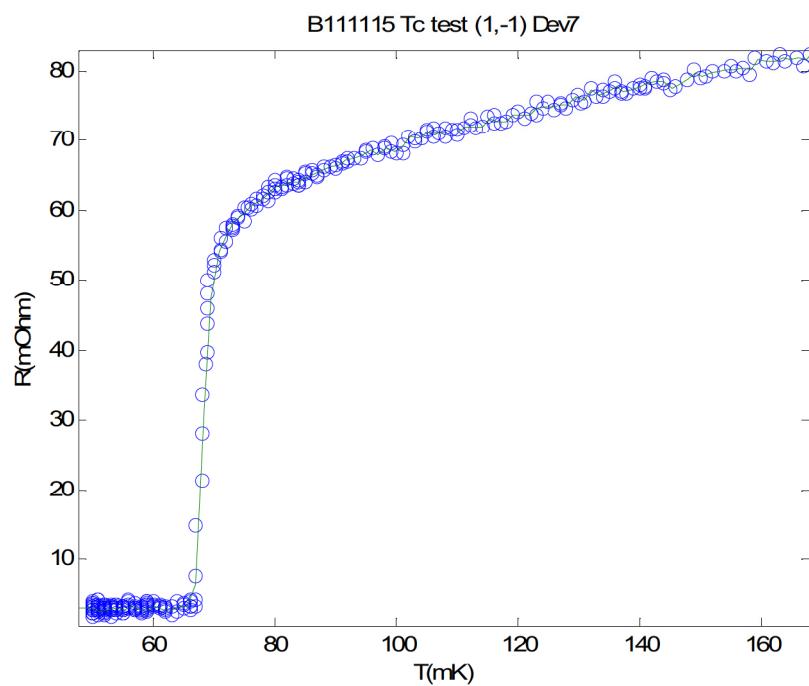
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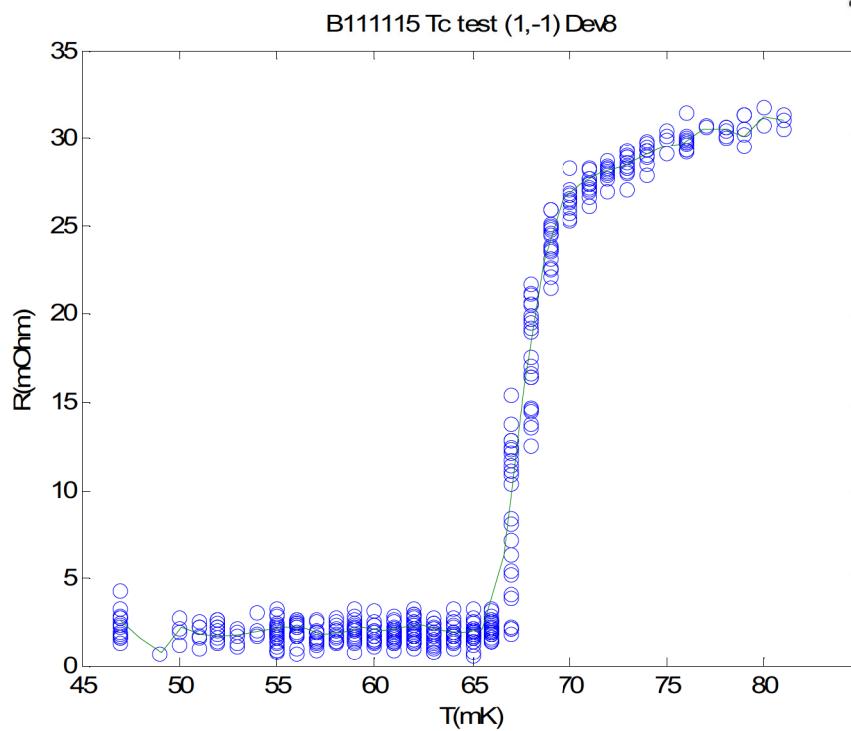
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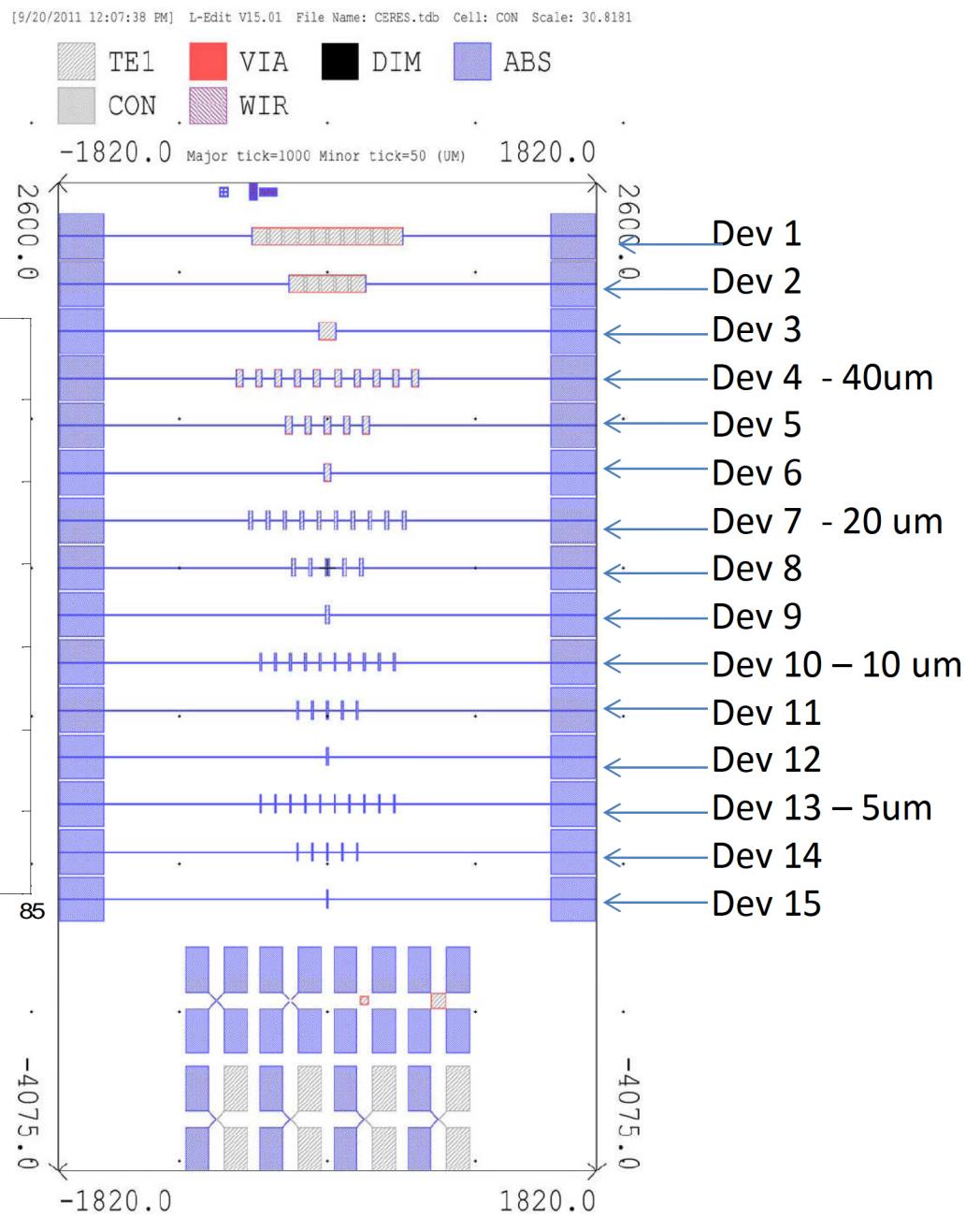
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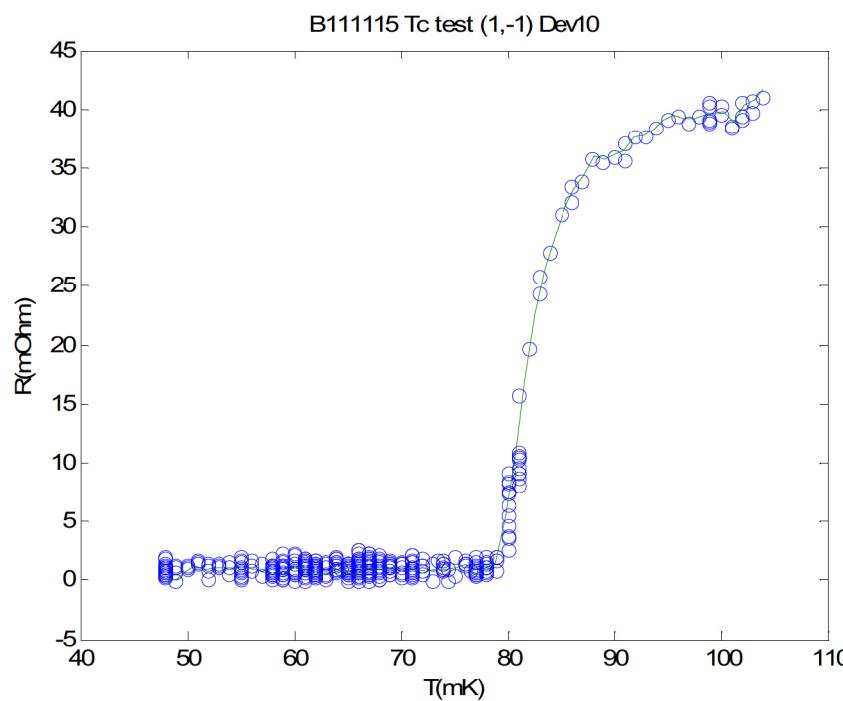
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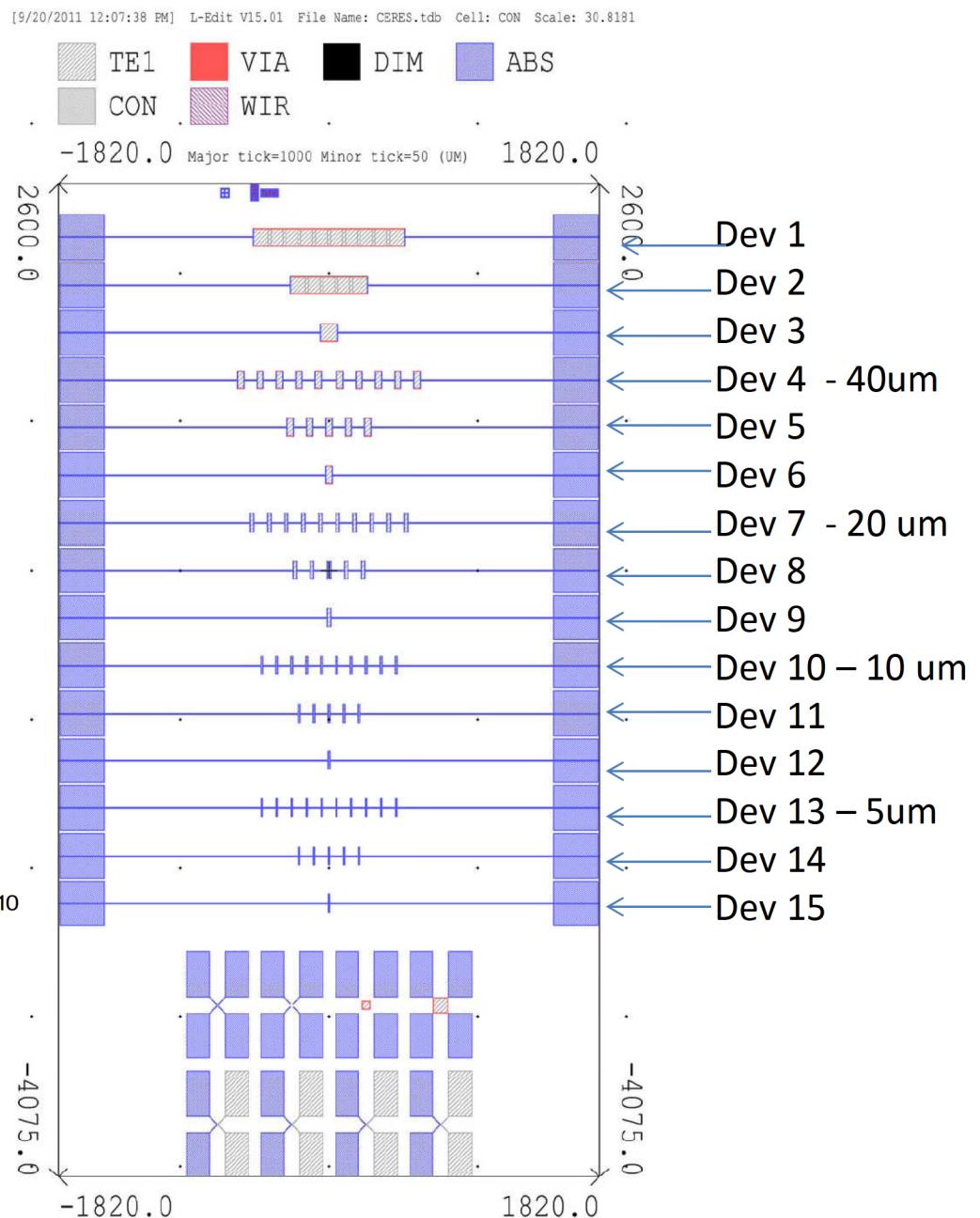
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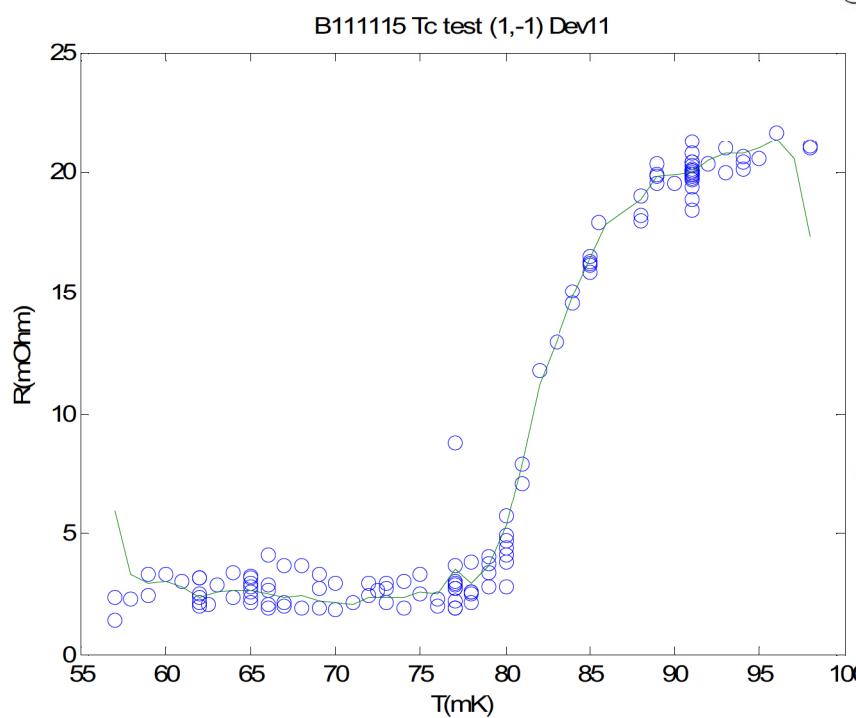
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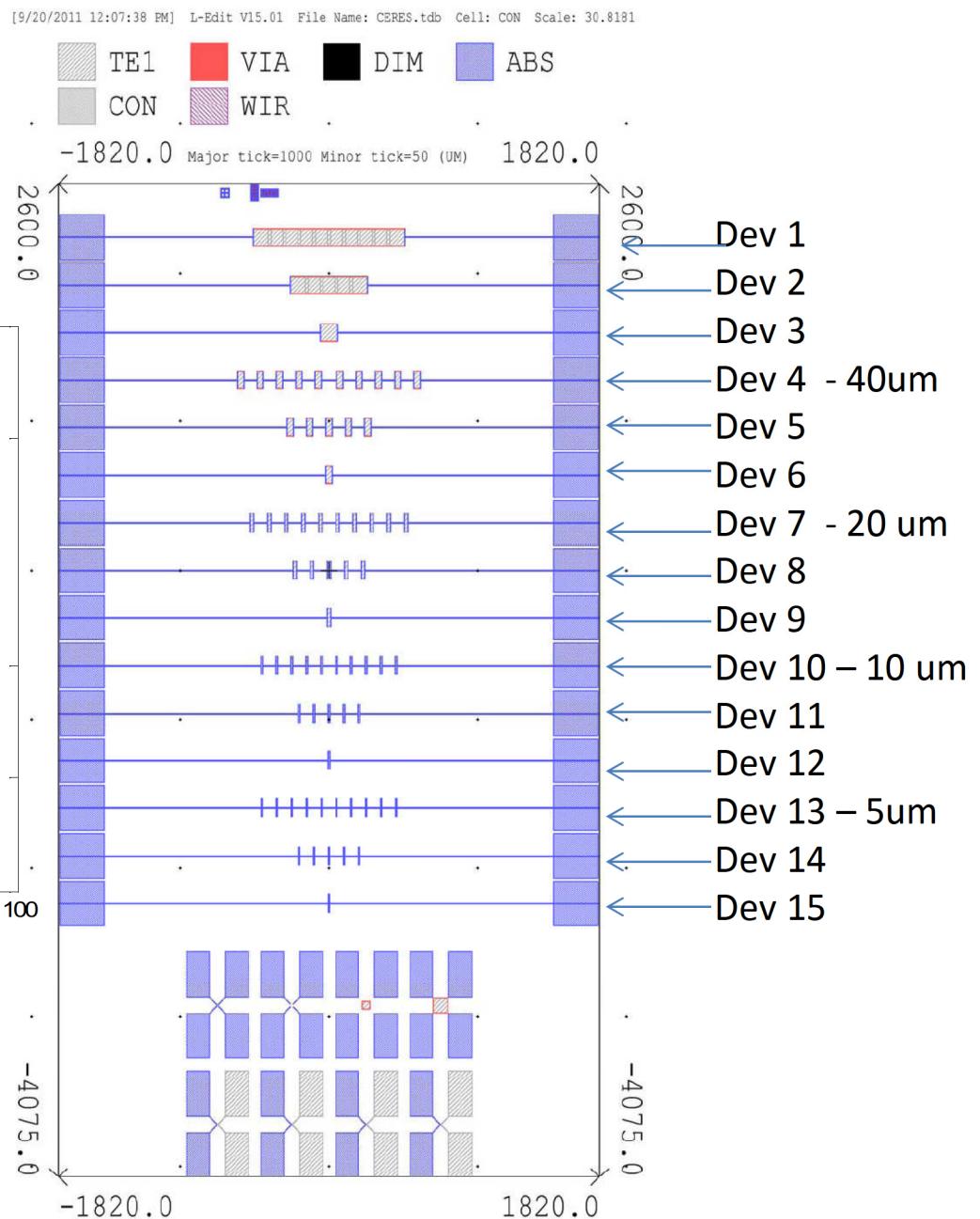
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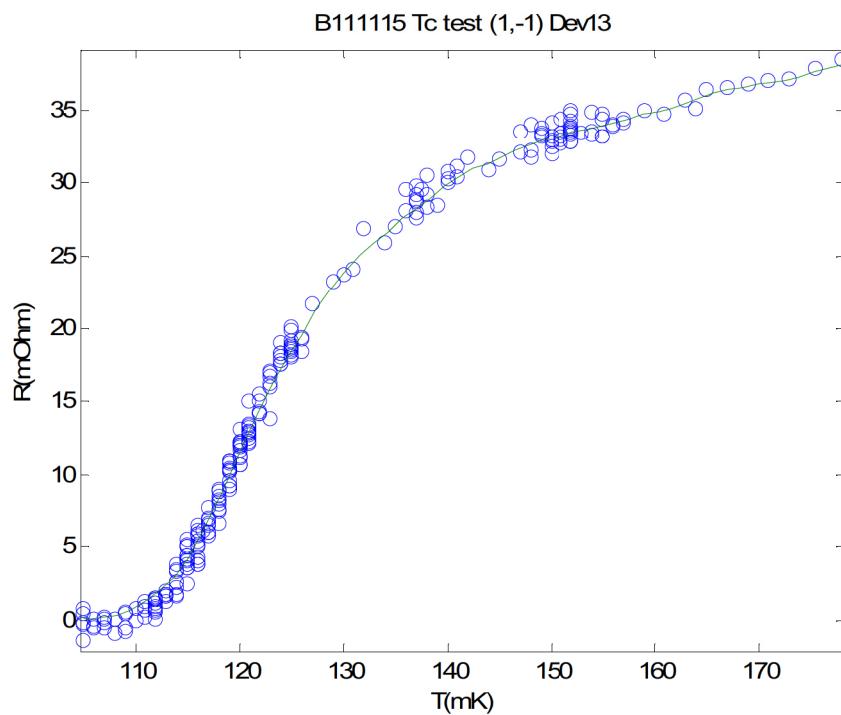
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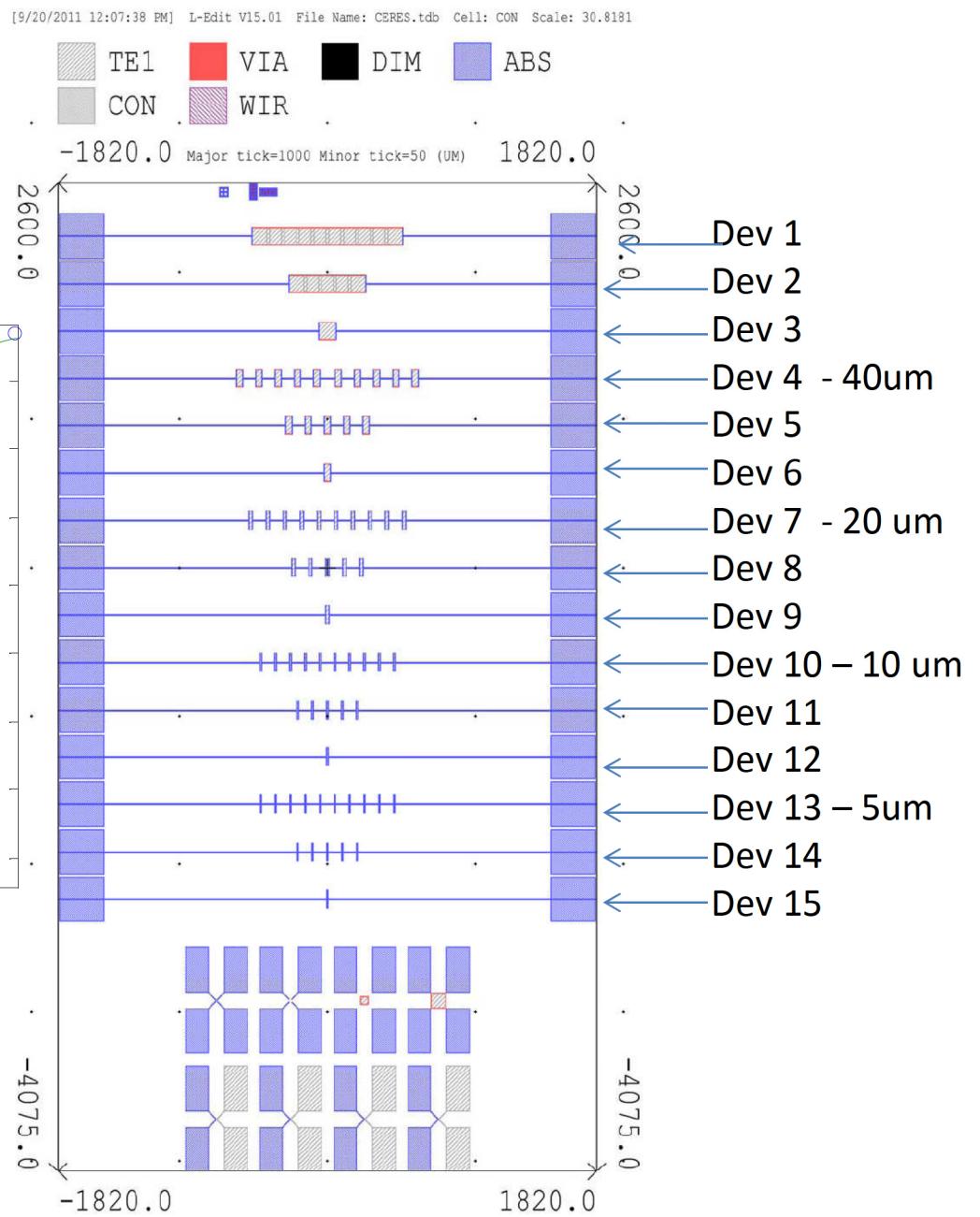
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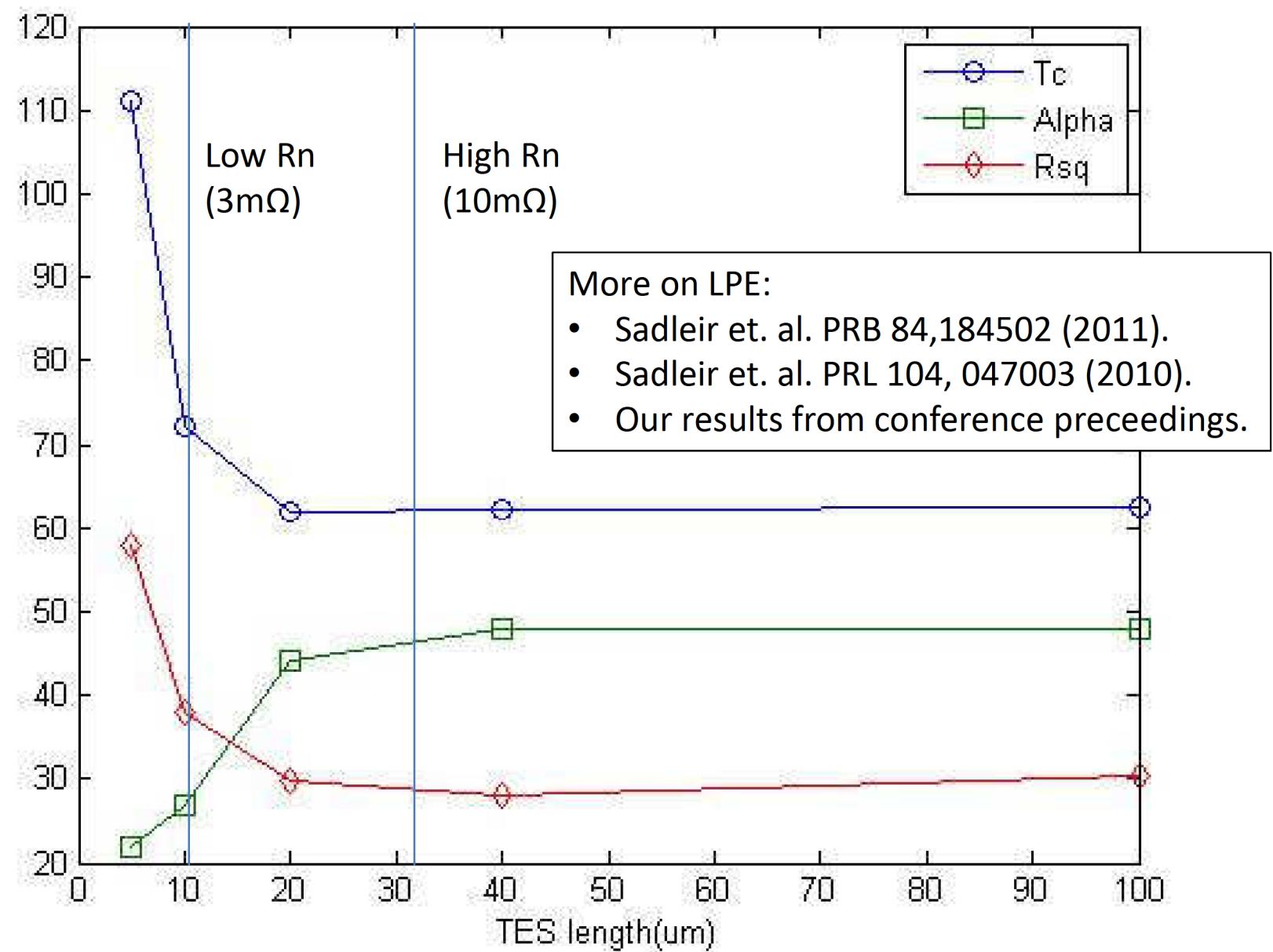
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B111115 BLISS Tc test design  
Mo/Cu/Ti recipe  
TiN wire



# Longitudinal proximity effects (LPE)



# G, C for BLISS-like NTDs



Given a background limited device ( $G=15\text{fW/K}$ ) with  $T_c=65\text{mK}$ , and  $G \sim T^{1/2}$ , we need:

$$P_{\text{dark}} < 200\text{aW at } 50\text{mK}.$$

- To gauge  $P_d$  correctly, you must know  $T_c$ !

## Other constraints:

- For the small  $G$  values of BLISS, thermistor is significant fraction of heat capacity.  
**→thermistor size will affect speed (through C and  $\alpha$ ).**
- Thermistor size (volume, length) will affect  $R_n$ .  $R_n$  affects MUX penalty.  
**→thermistor size will affect MUX penalty.**

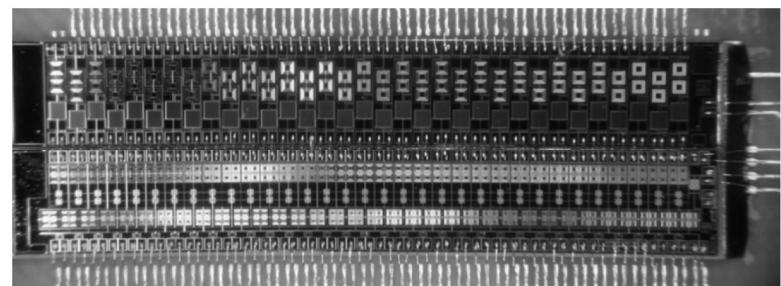
# Multiplexed noise estimate



Time-domain multiplexing

<i>Sensor material:</i>	Bilayer Mo/Au	
	<i>Low R<sub>N</sub></i>	<i>High R<sub>N</sub></i>
<i>R<sub>operation</sub></i> :	3mΩ	10mΩ
<i>L (SQUID + Nyquist)</i> :	1.5μH	6μH
<i>S<sub>DC</sub> (10<sup>9</sup> A/W)</i>	2.5	1

- SQUID multiplexer & shunt (Nyquist) chips from NIST (Boulder, CO).
- MCE from UBC.



## Noise budget:

Band (μm)	357	230	148	92	53
NEP <sub>phonon</sub> (10 <sup>-20</sup> W/Hz <sup>1/2</sup> )	4.61	2.50	2.47	2.55	2.48
NEP <sub>Johnson</sub> (10 <sup>-20</sup> W/Hz <sup>1/2</sup> )	0.58	0.31	0.31	0.32	0.31
NEP <sub>shunt</sub> (10 <sup>-20</sup> W/Hz <sup>1/2</sup> )	0.65	0.35	0.35	0.36	0.35
NEP <sub>photon</sub> (10 <sup>-20</sup> W/Hz <sup>1/2</sup> )	5.05	2.41	2.58	2.39	3.07
NEP <sub>tot</sub> (no SQUID) (10 <sup>-20</sup> W/Hz <sup>1/2</sup> )	6.90	3.51	3.60	3.53	3.97
NEP <sub>det</sub> (aliased) (10 <sup>-20</sup> W/Hz <sup>1/2</sup> )	7.10	3.63	3.72	3.65	4.08
NEP <sub>SQUID</sub> (aliased) (10 <sup>-20</sup> W/Hz <sup>1/2</sup> )	0.97	0.53	0.52	0.54	0.52
NEP <sub>total</sub> (MUXED) (10 <sup>-20</sup> W/Hz <sup>1/2</sup> )	7.17	3.67	3.75	3.69	4.11
MUX penalty	1.04	1.05	1.04	1.05	1.03

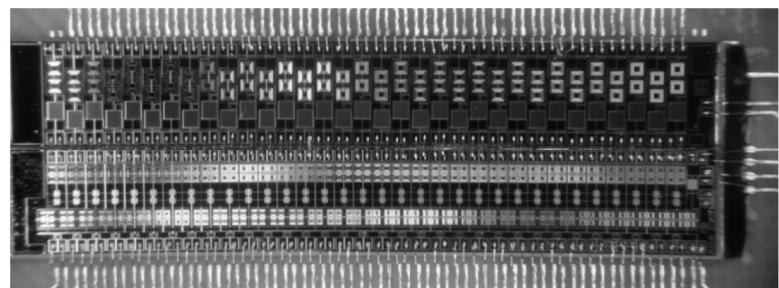
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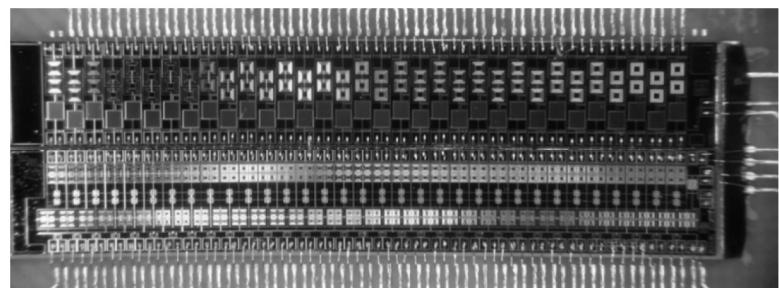
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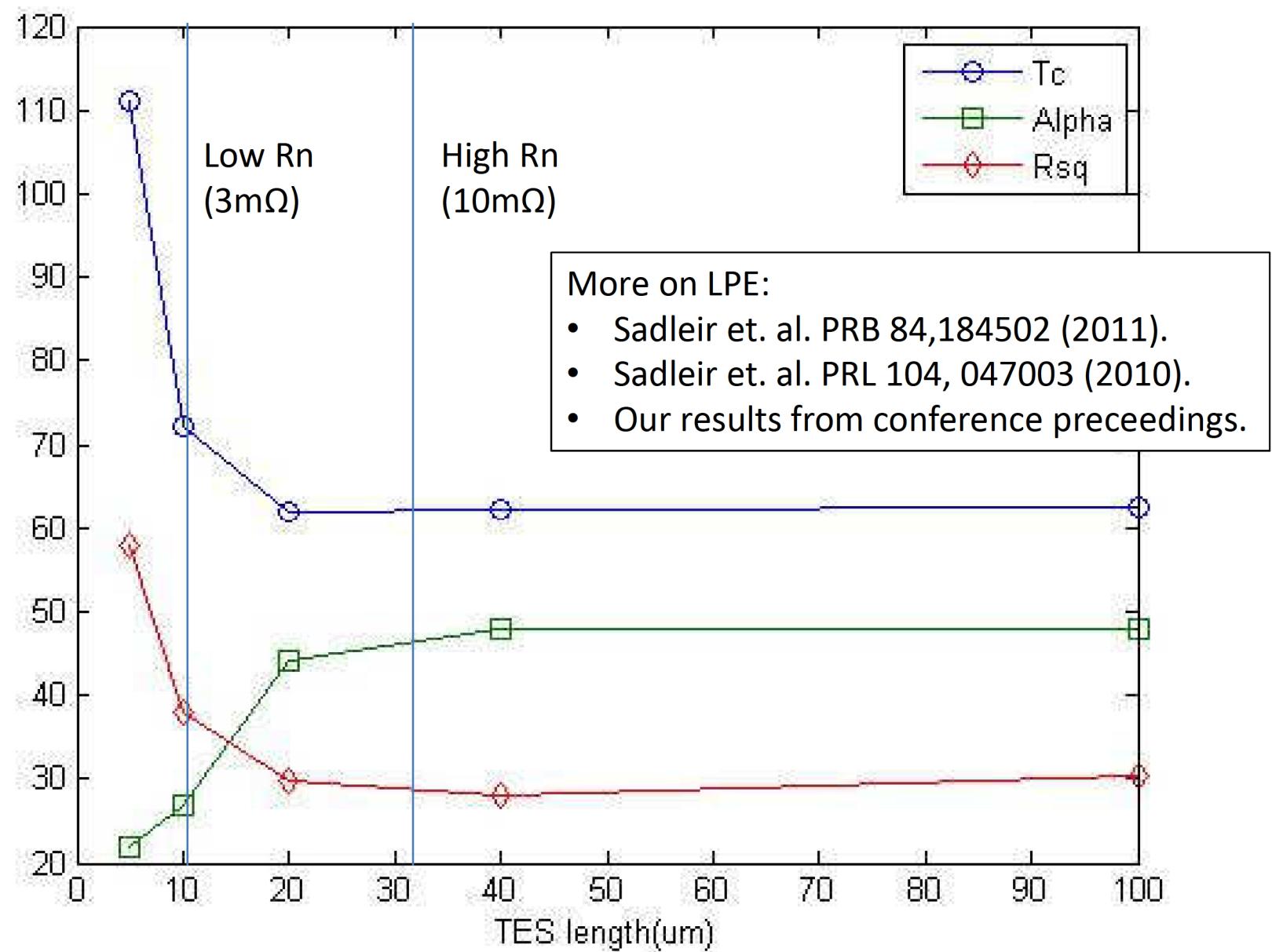


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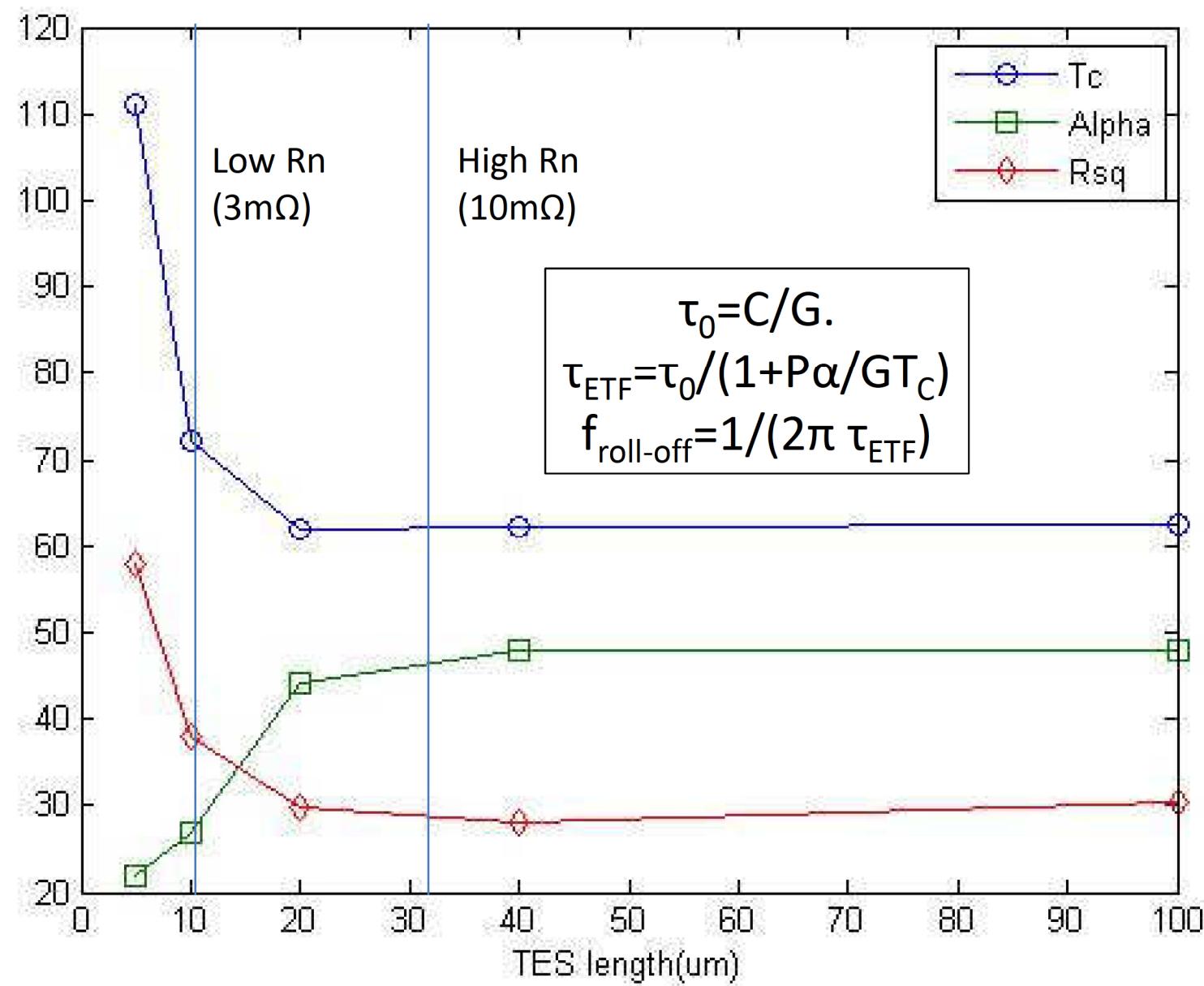
Increases to ~1.15 for high R<sub>N</sub>!



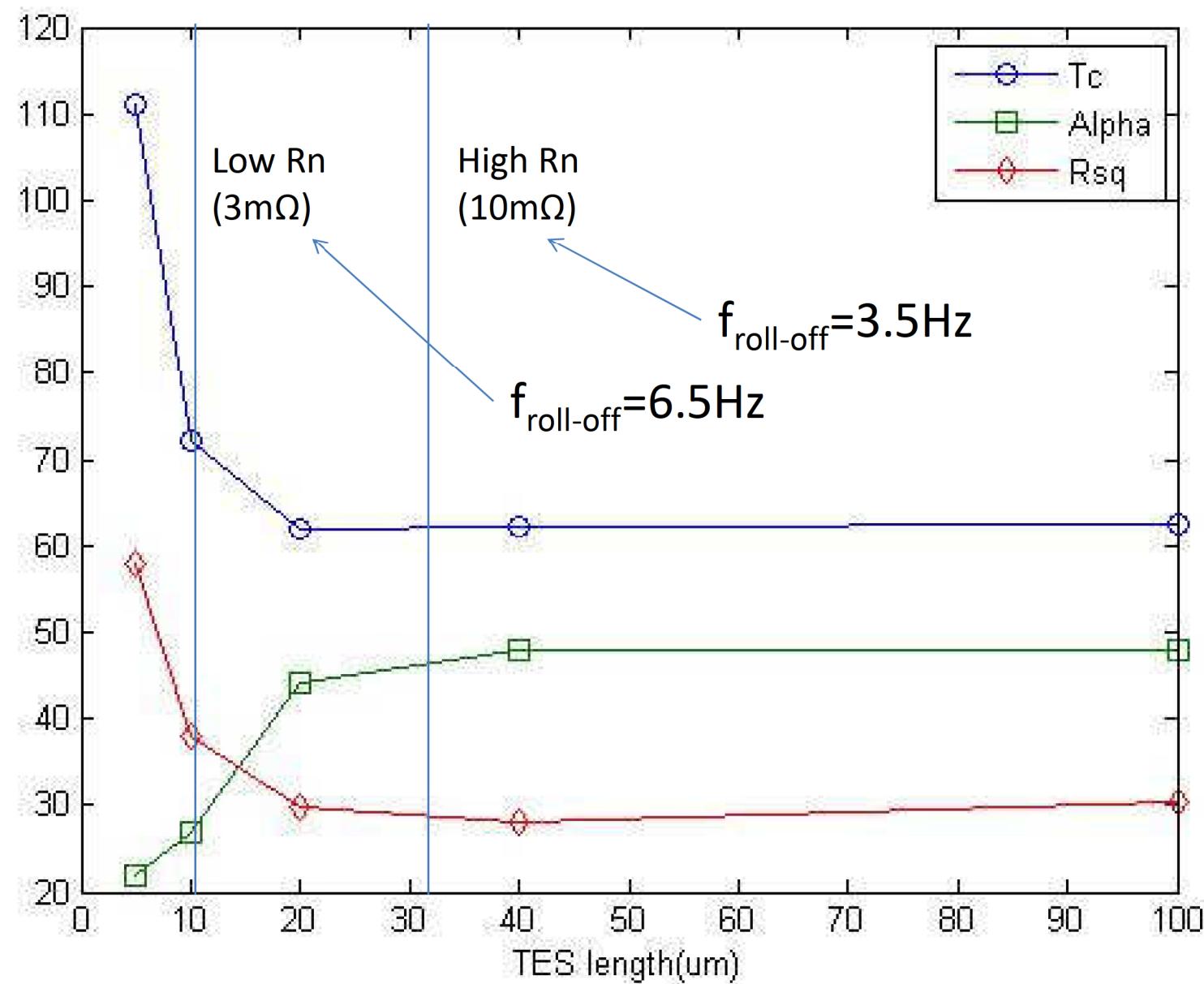
# Longitudinal proximity effects (LPE)



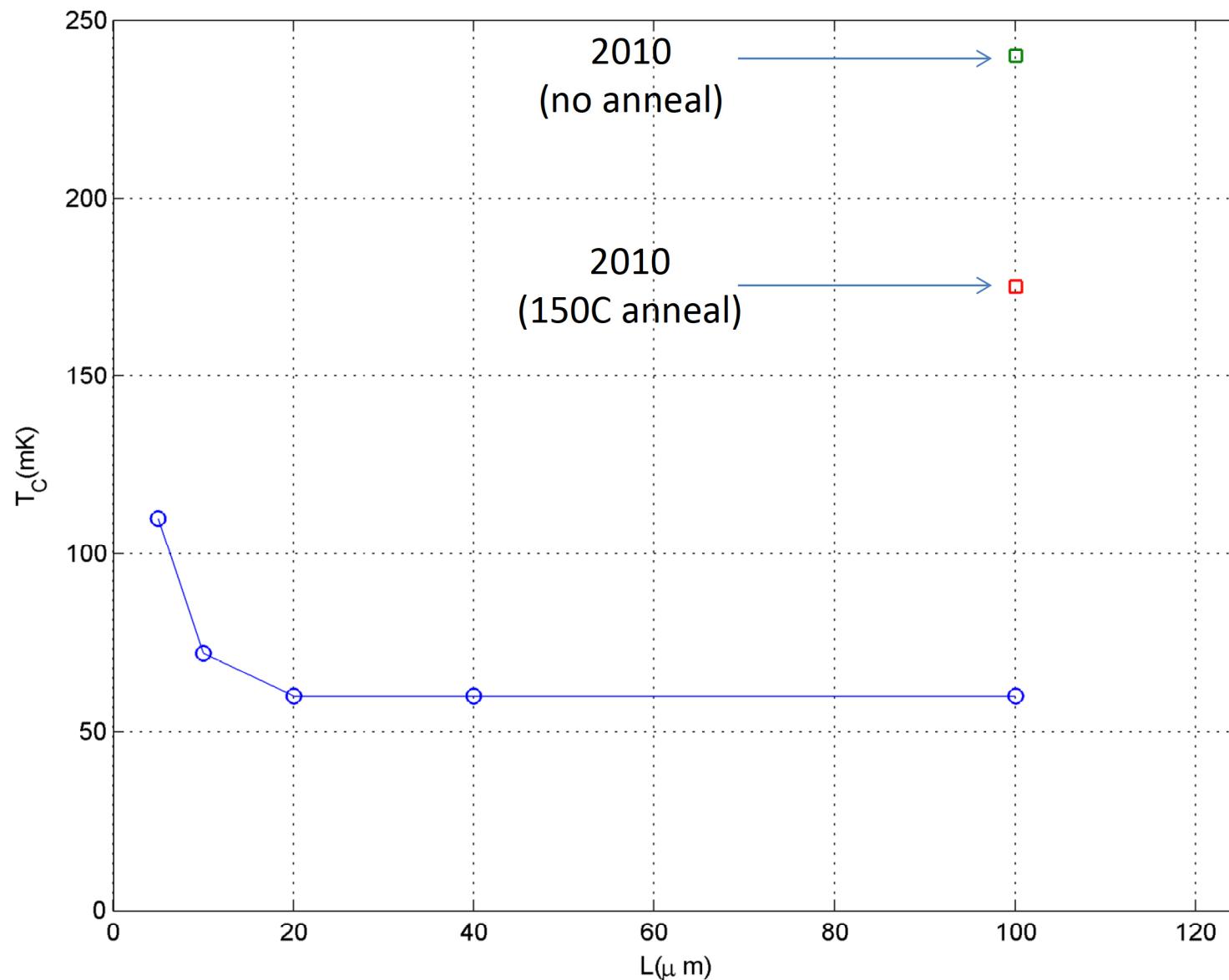
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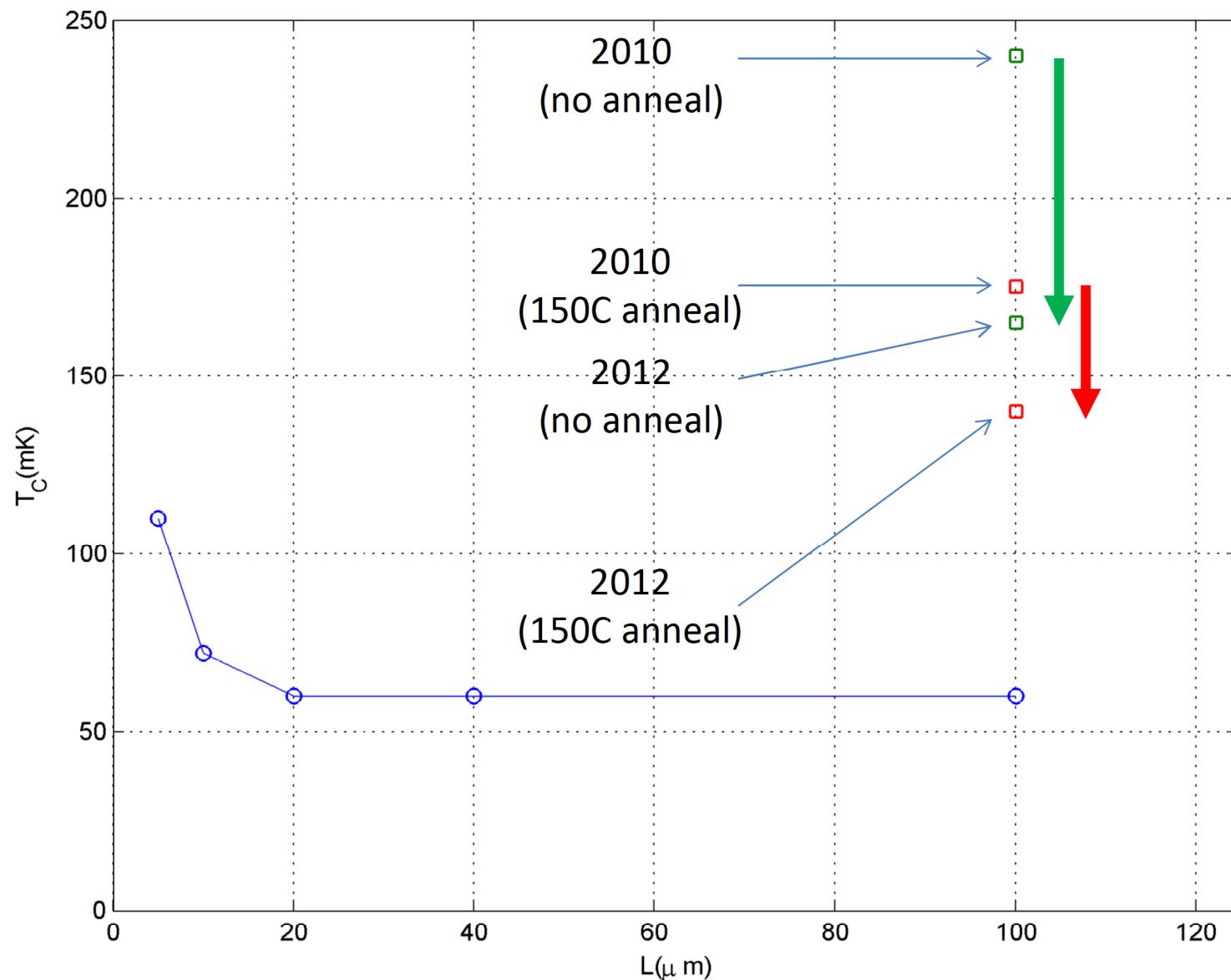
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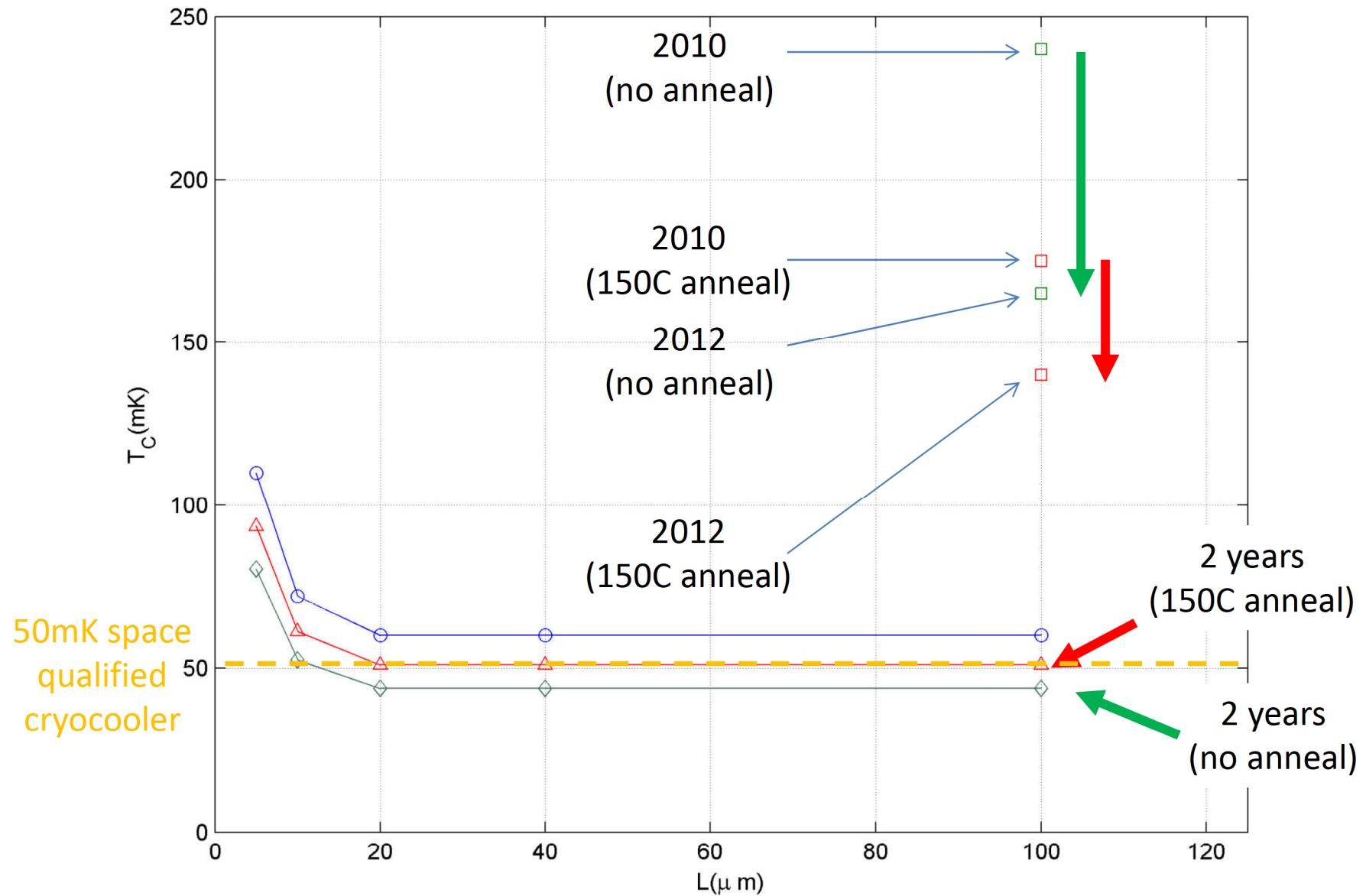
# Longitudinal proximity effects

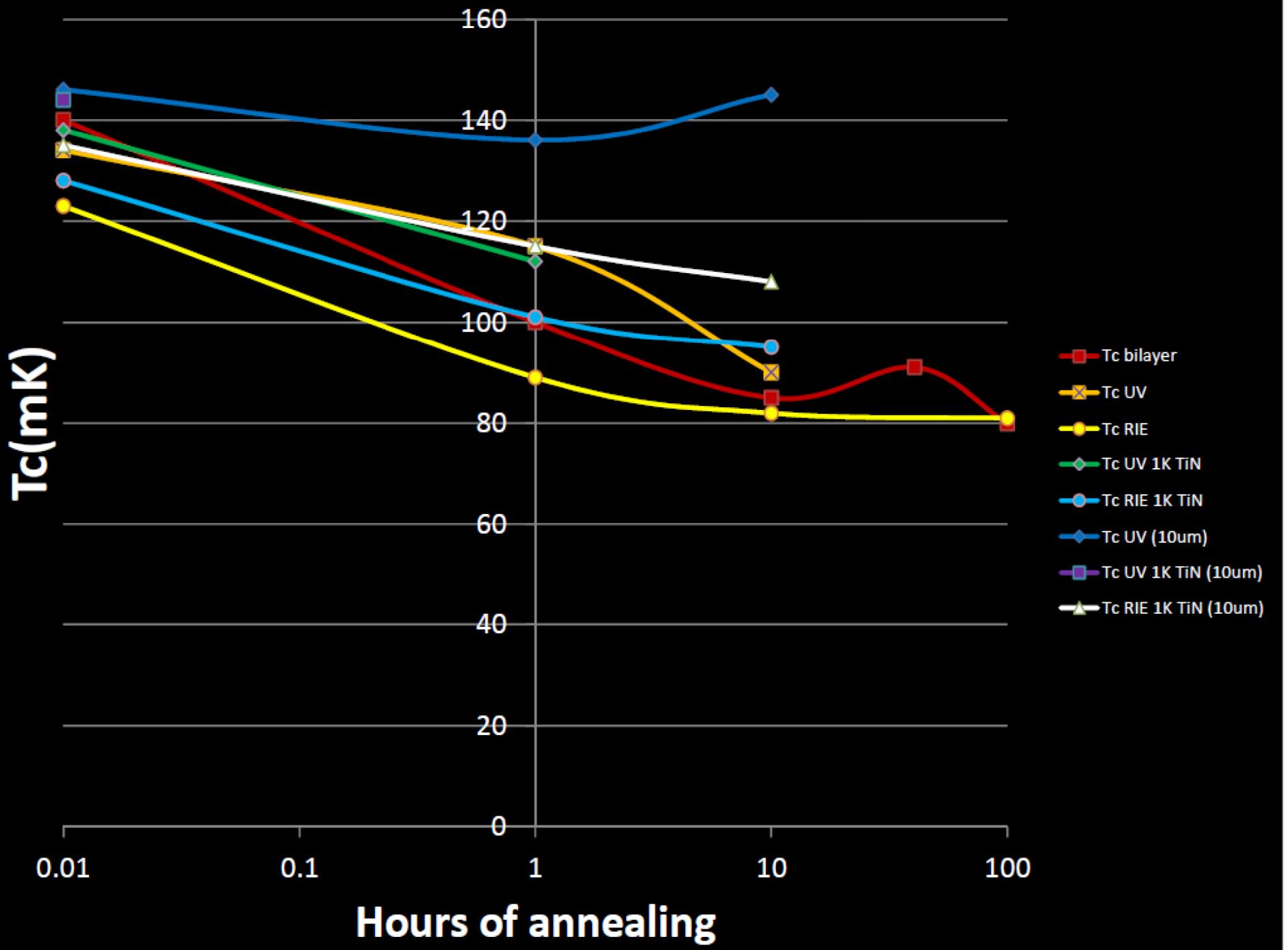


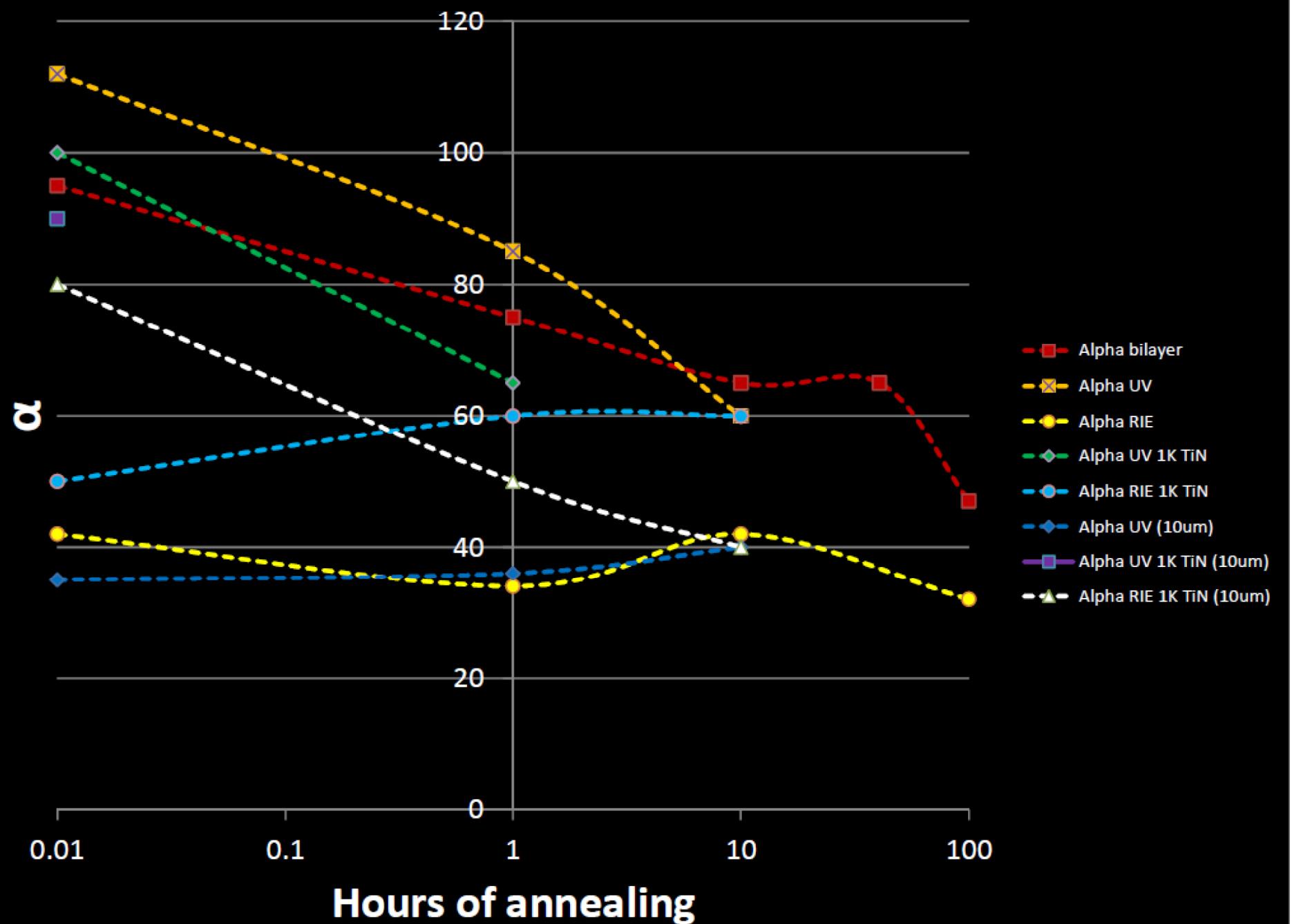
# Longitudinal proximity effects



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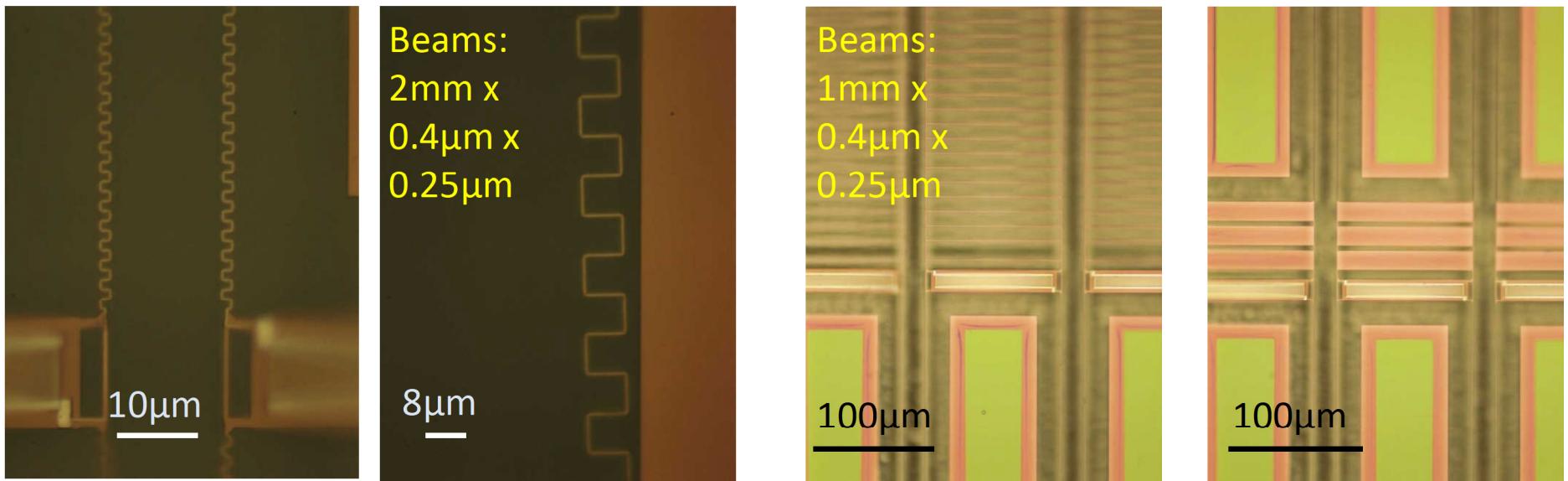
# Outline

1. Motivation and intro to TESs.
2. BLISS Specifications—tolerance to dark power
3. Measuring stray (dark) power— $T_c$  (alpha) and G measurements
  - a. Overview two methods: JTD vs. TES
  - b. TES arrays: measurement complications for  $P_d$ ,  $T_c$ , and alpha.
4. Results:  $P_d$  compare, NEP, tau, 1/f issues

Paths forward to measure Pd:

1. Use inert, elemental superconductor TES arrays ( $T_c$  stays constant).
2. Design bilayer arrays with varying G values, Rn values, and  $T_c$  test structures.

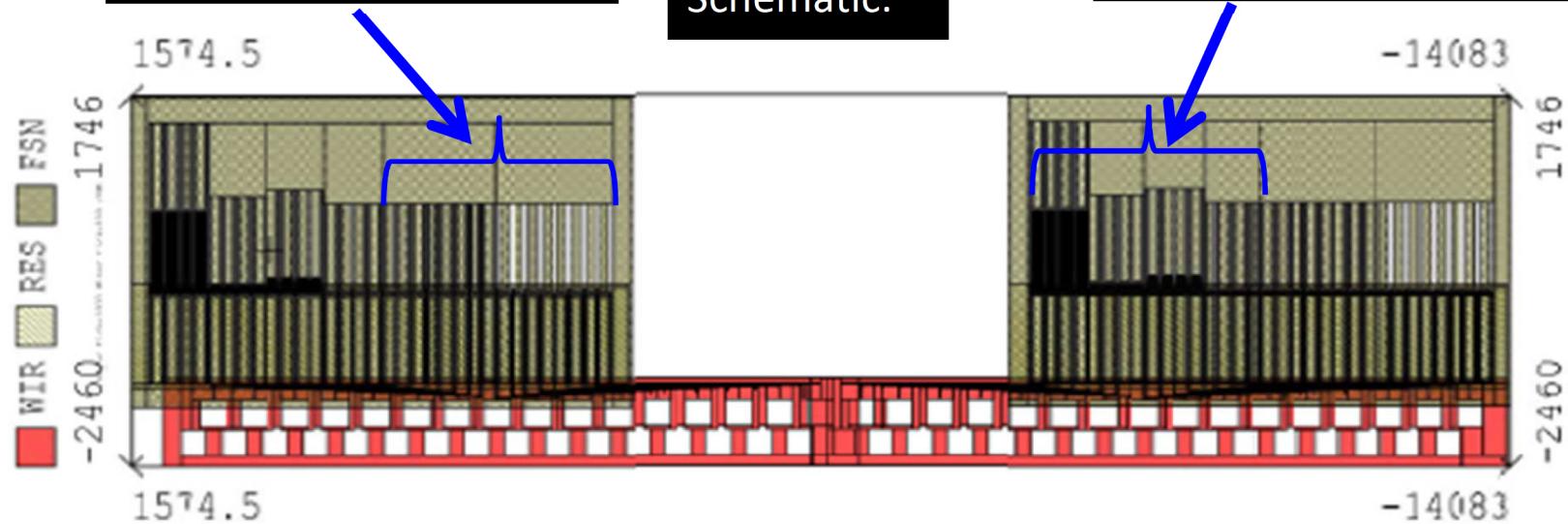
# Ir BLISS arrays ( $T_c=135\text{mK}$ )



Meandered beams , no  
absorber(connected on left)

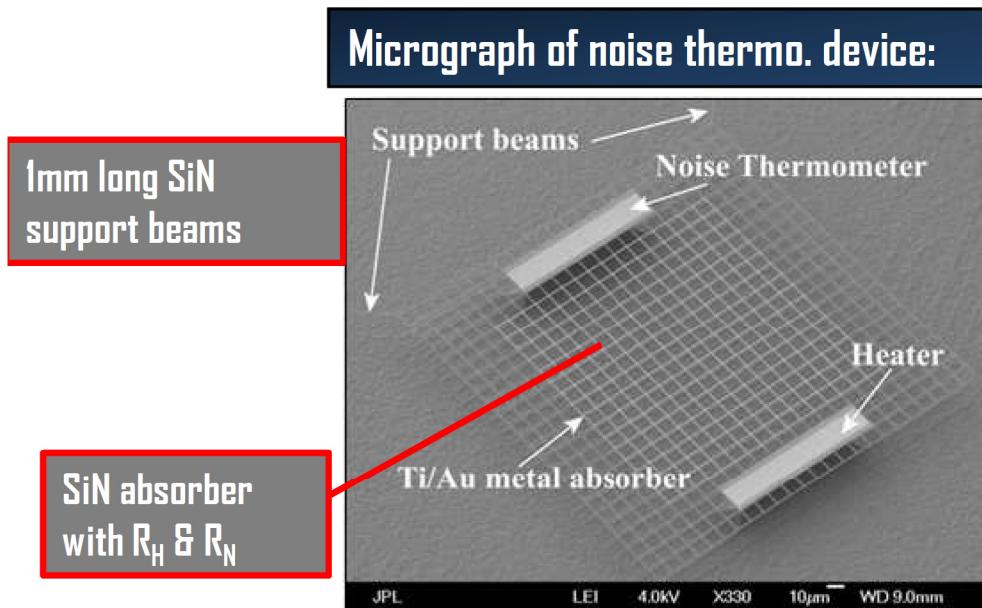
Schematic:

Straight beams, different  
absorbers (connected on right)



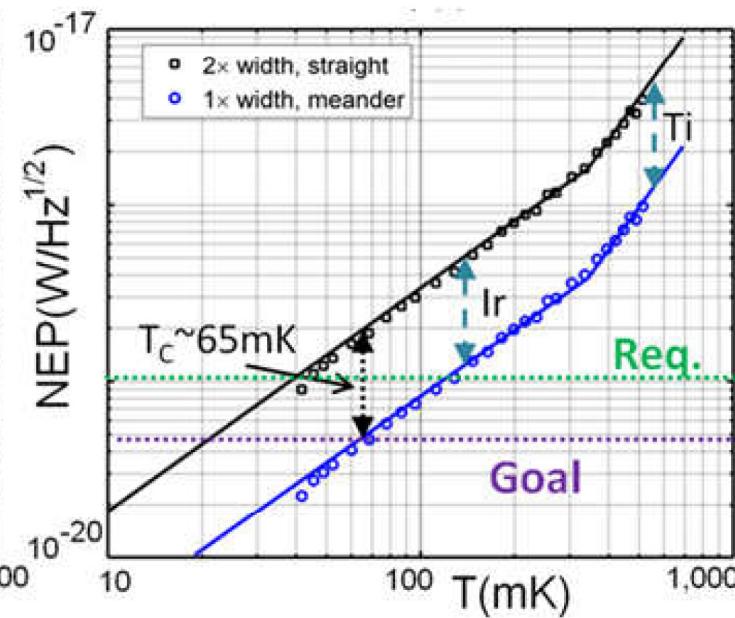
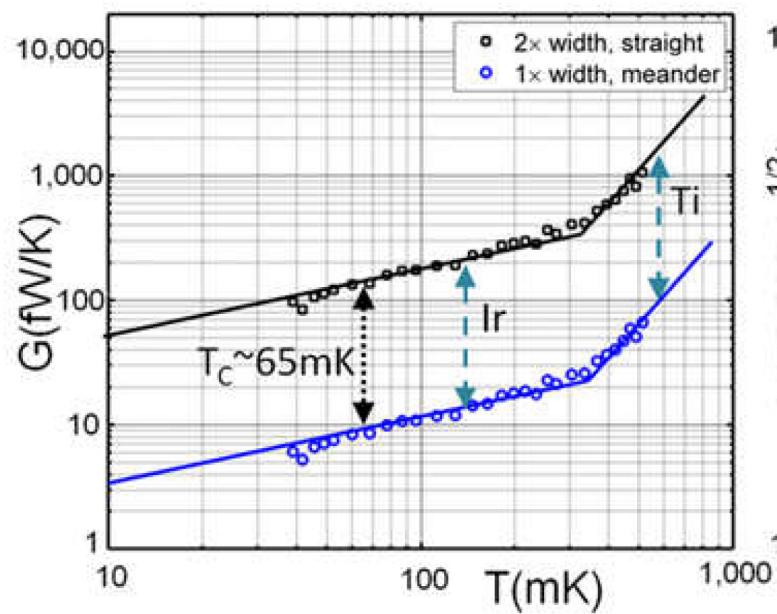


# Experimental setup: how small is G?

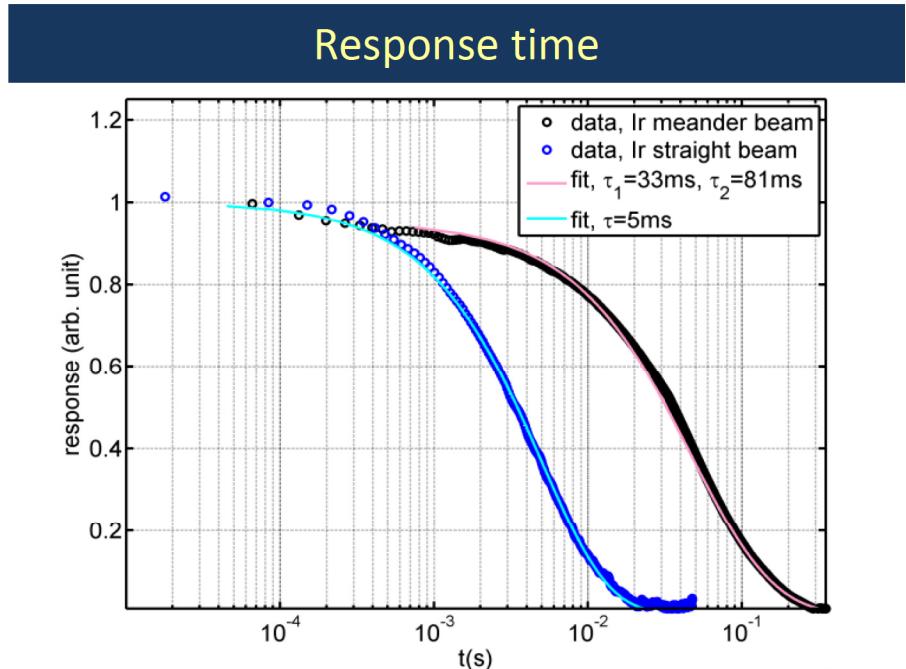
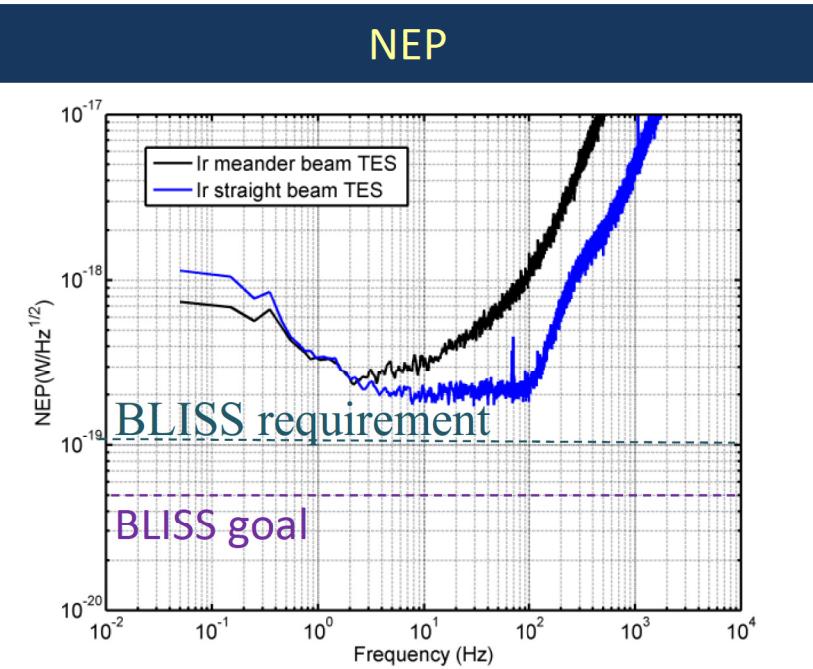


- Apply power:  $P=I^2R_H$
- Measure temp:  $4k_bT/R_N$
- Thermal conduct.:  $G=dP/dT$

$$NEP_{TFN} = \sqrt{4k_B T_C^2 G}$$



# Best results on BLISS arrays: Ir ( $T_C=130\text{mK}$ )



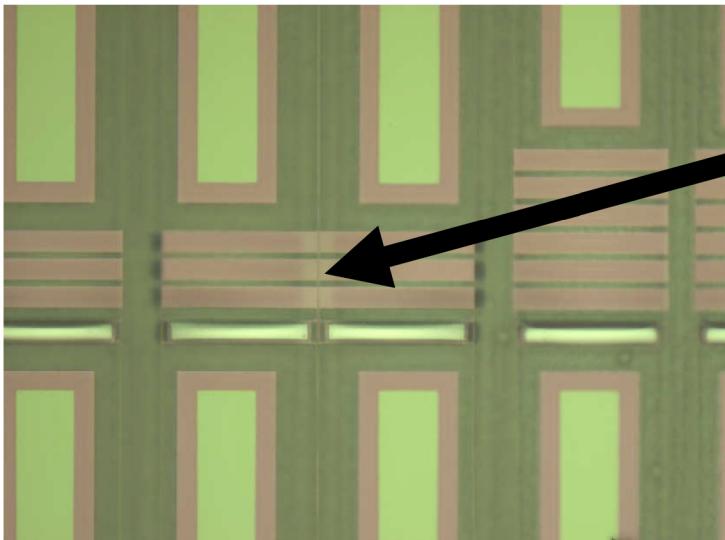
Meander beams & L/R filter (BW: 150kHz).

Straight beams & L/R filter (BW: 150kHz).

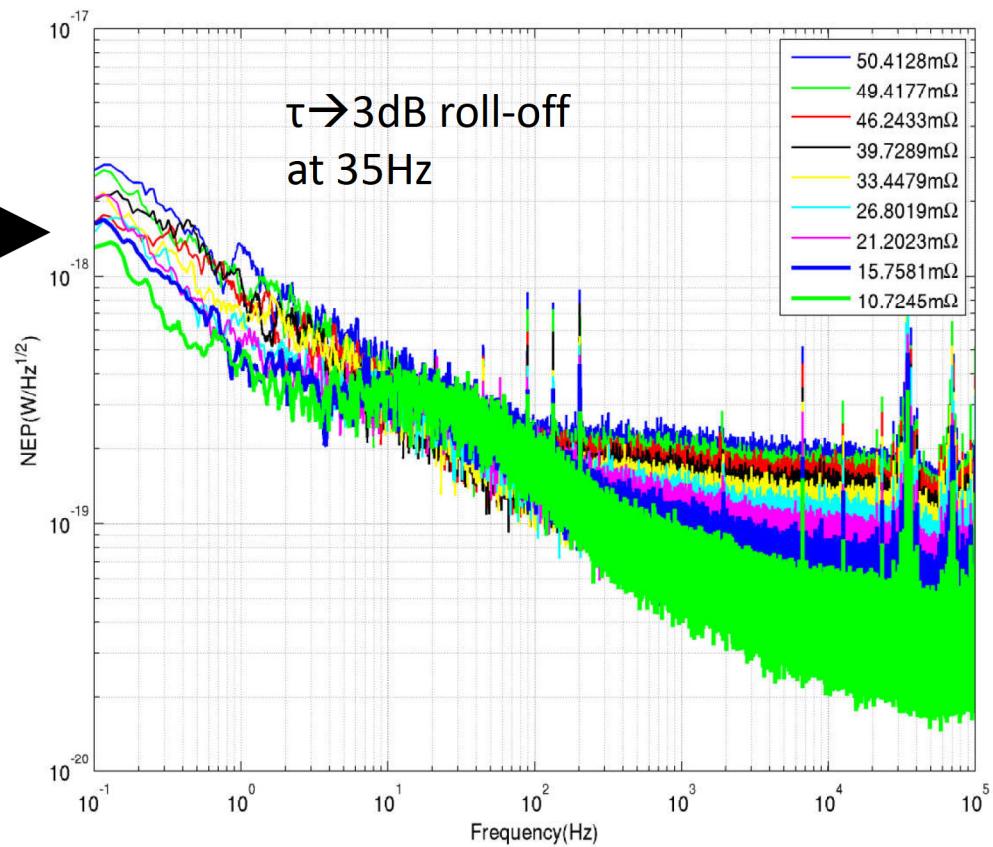
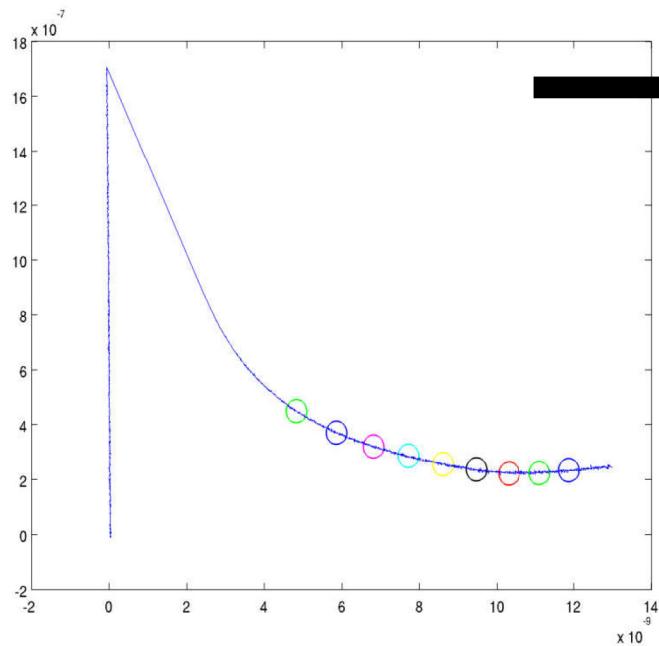
Straight beams &  $\pi$  filter (BW: ~15MHz).

Material ( $T_C$ )	Type	$G$ (fW/K)	$n$ ( $G^\sim T^n$ )	$P_{\text{dark}}$ (fW)	$\gamma$ (50mK)	$\text{NEP}_{\text{exp}}$ ( $10^{-19}\text{W}/\text{Hz}^{1/2}$ )	$\text{NEP}_{\text{meas}}$ ( $10^{-19}\text{W}/\text{Hz}^{1/2}$ )	$\tau$ (ms)	$\tau_{\text{Band6}}$ (ms)
Ir (130mK)	3M	35	0.5	0.9	0.71	1.5	2.5	7.9	131
Ir (130mK)	2M	30	0.5	0.9	0.71	1.4	2.5	16.5	274
Ir (130mK)	2M	30	0.5	0.9	0.71	1.4	2.5	30.2	502
Ir (130mK)	1M	35	1.5	0.9	0.59	1.4	2.5	32.3	537
Ir (130mK)	NP	110	0.5	2.5	0.71	2.7	2.5	4.8	79
Ir (130mK)	3P	115	1.5	2.0	0.59	2.5	2.5	5.2	86
Ir (130mK)	6P	120	1.5	1.5	0.59	2.6	2.6	5.0	83
Ir (130mK)	6P	120	1.5	1.5	0.59	2.6	2.6	4.7	77
Ir (130mK)	6P	110	1.5	1.0	0.59	2.5	2.5	4.5	76
Ir (130mK)	6P	110	1.5	1.0	0.59	2.5	2.5	4.7	78
Ir (130mK)	6P	120	0.5	4.8	0.71	2.8	2.8	1.3	22
Ir (130mK)	6P	110	0.5	4.8	0.71	2.7	2.9	3.7	61
Ir (130mK)	NP	140	0.5	4.0	0.71	3.0	3	1.5	24
Ir (130mK)	NP	100	0.5	4.6	0.71	2.6	2.6	3.3	55

# Best results on BLISS arrays: Ir ( $T_C=130\text{mK}$ )

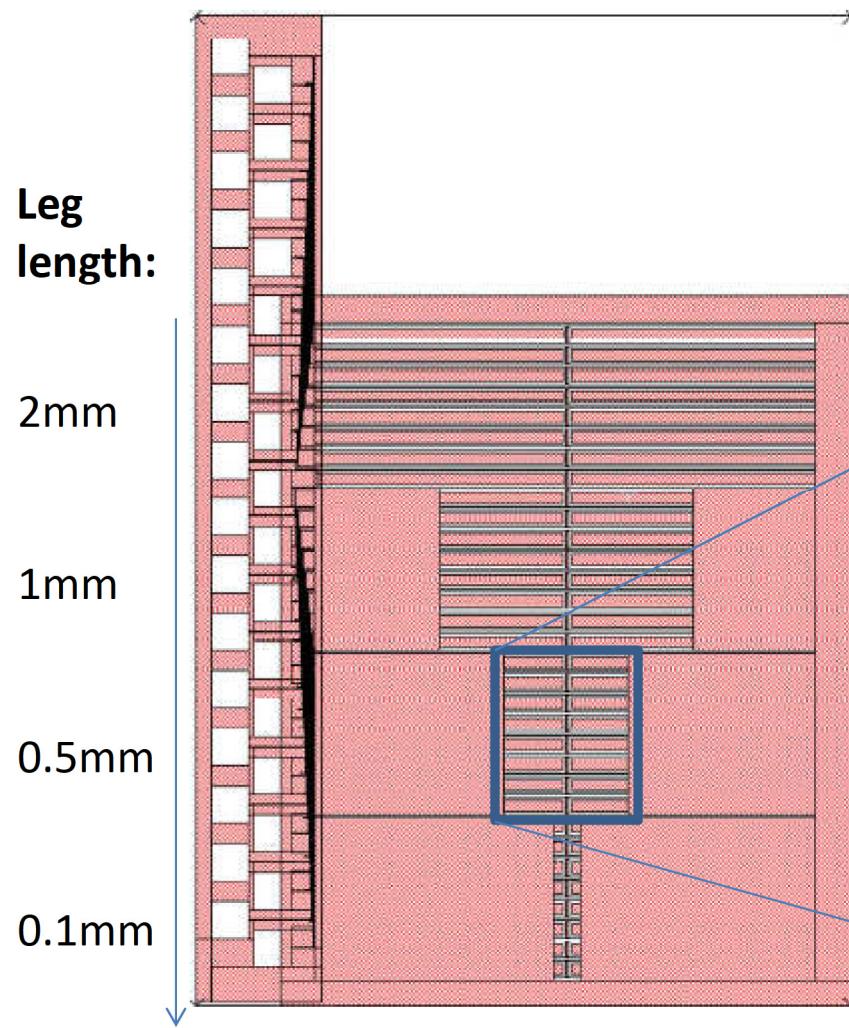


- Did witness some devices sticking together (picture from SRON).
- Were able to confirm low G, NEP on pristine device.



# G, $R_N$ array: Mo/Cu (Nominal $T_C = 125\text{mK}$ & $225\text{mK}$ ).

Variable G,  $R_N$  Array Sketch:

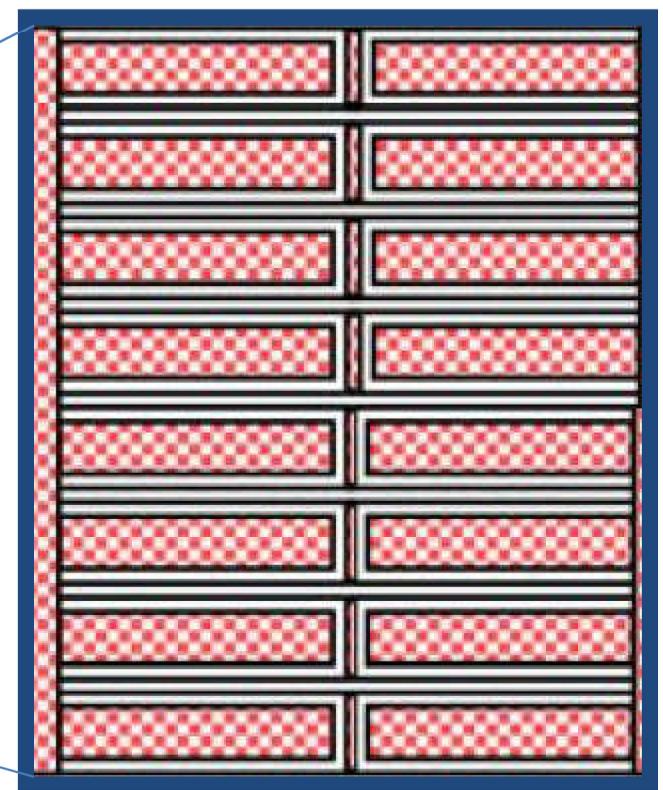


- Built an array with varying leg lengths → vary G with same Mo/Cu recipe.
- Variable widths to examine  $T_C$ , NEP,  $\tau$  dependence on width.

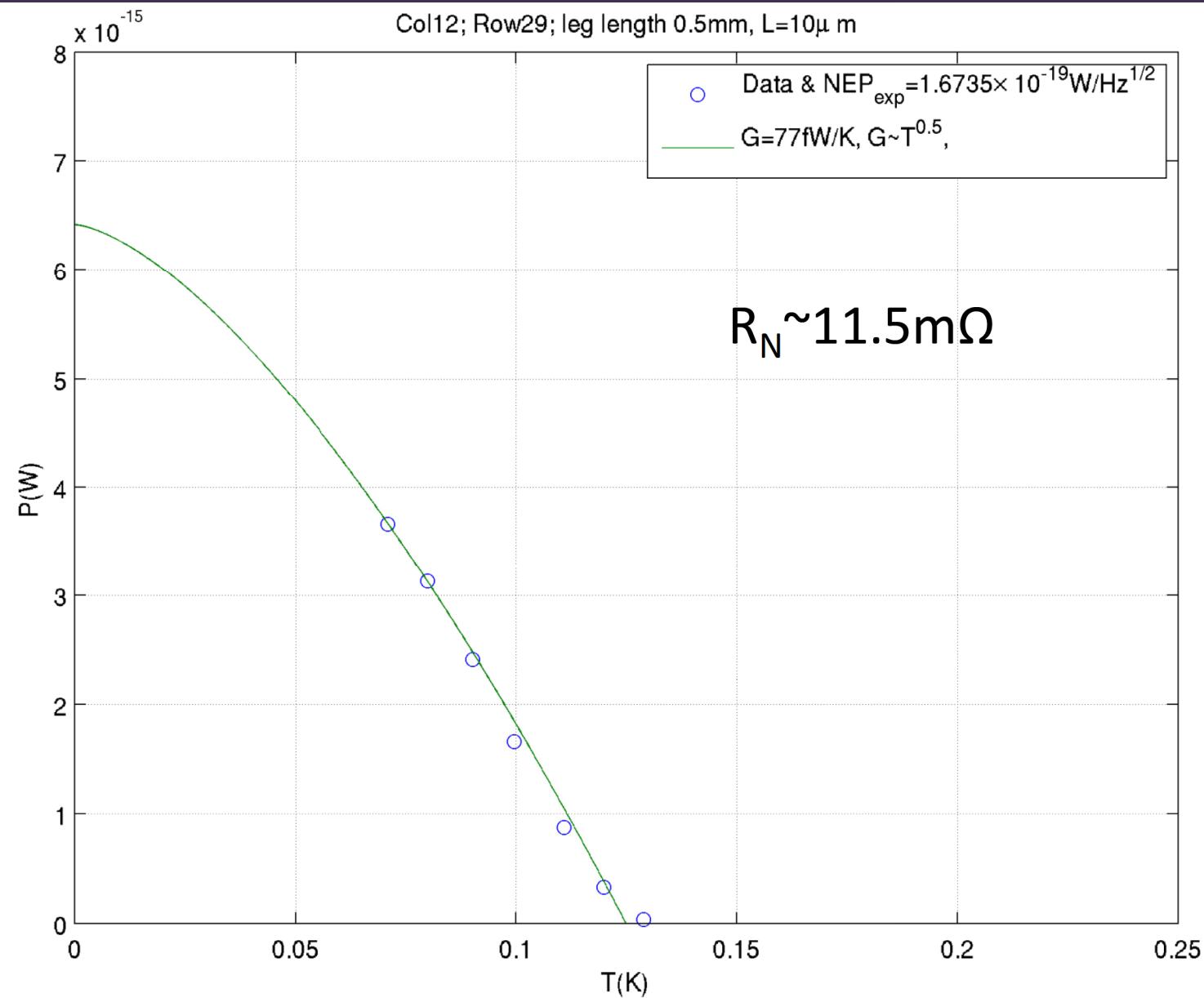
Vary  
width  
for  $R_N$ :

$10\mu\text{m}$  width

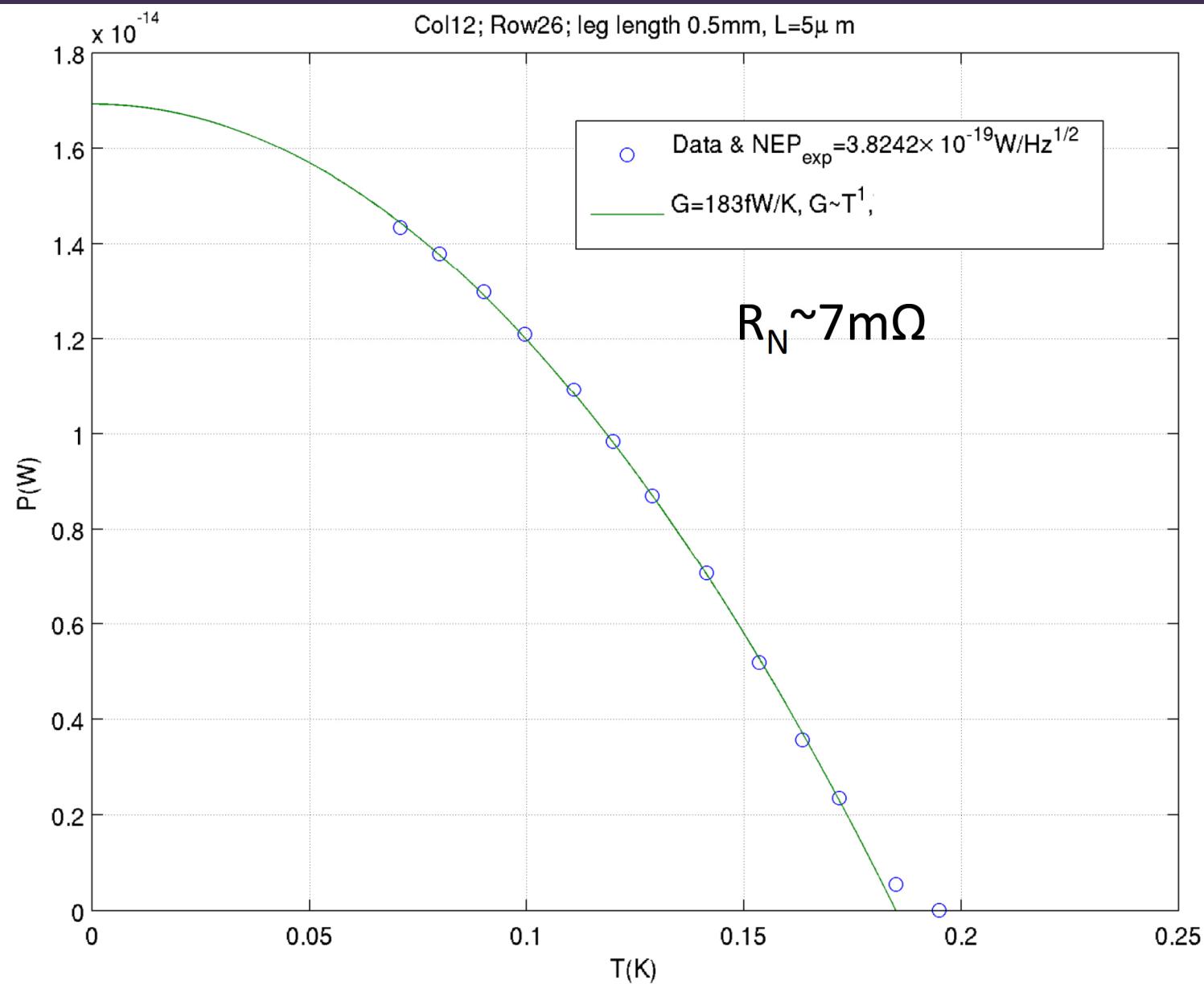
$5\mu\text{m}$  width



# G, R<sub>N</sub> array: ½ mm legs, 10µm width



# G, R<sub>N</sub> array: ½ mm legs, 5µm width



# G, R<sub>N</sub> array: Results comparison

- Tried to add Eccosorb to boxes for further optical dark power reduction.
- Many titanium TESs did not transition with Eccosorb → previously had transitioned.

Mo/Cu :

5μm width:

*0.5mm legs*      **183 fW/K**

*1mm legs*      **135 fW/K**

10μm width:

*0.1mm legs*      **605 fW/K**

*0.5mm legs*      **77 fW/K**

*2mm legs*      **965 fW/K**

Likely a touch or sticking!

Dark power is about 1fW.

Ir :

10μm width:

*2mm legs*      **1.25 fW/K**

# G, R<sub>N</sub> array: Results comparison

- Tried to add Eccosorb to boxes for further optical dark power reduction.
- Many titanium TESs did not transition with Eccosorb → previously had transitioned.

Mo/Cu :

5μm width:

*0.5mm legs*      **185mK**

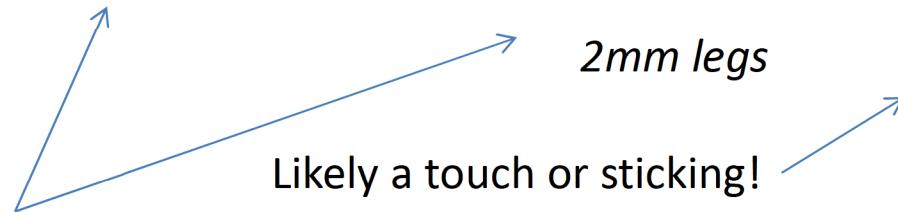
*1mm legs*      **225mK**

10μm width:

*0.1mm legs*      **205mK**

*0.5mm legs*      **125mK**

*2mm legs*      **105mK**



Likely a touch or sticking!

- Temperature when P→0.
- Value varies wildly → Eccosorb causing local variations/problems.

Ir :

10μm width:

*2mm legs*      **1.25 fW/K**

# MoCu, 0.5mm, 1/10<sup>th</sup> sq, MUX09

$T_c \sim 135$  mK

$G_c \sim 65$  fW/K

$\beta \sim 0.5$

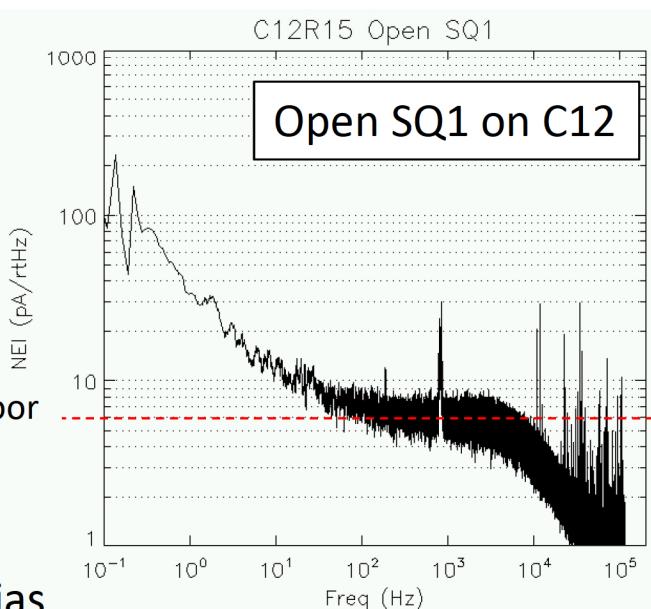
$R_n \sim 10\text{-}12$  mOhm

$NEP_G \sim 1.9E-19$  W/rtHz

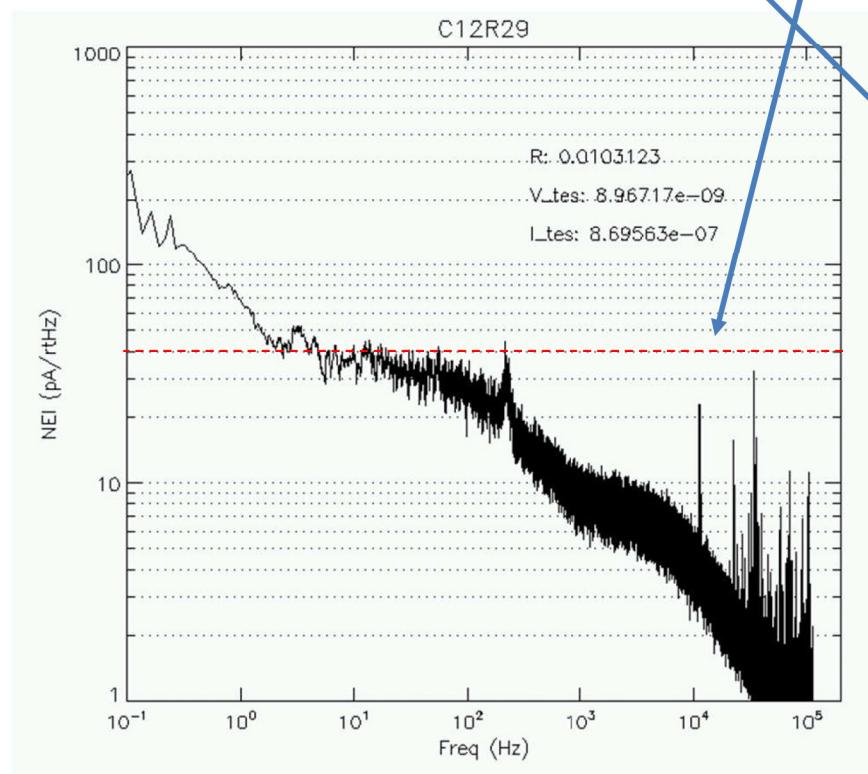
$$NEI_J \sim \sqrt{4kT_c/(R_n/2)}$$

$$\sim 40 \text{ pA/rtHz}$$

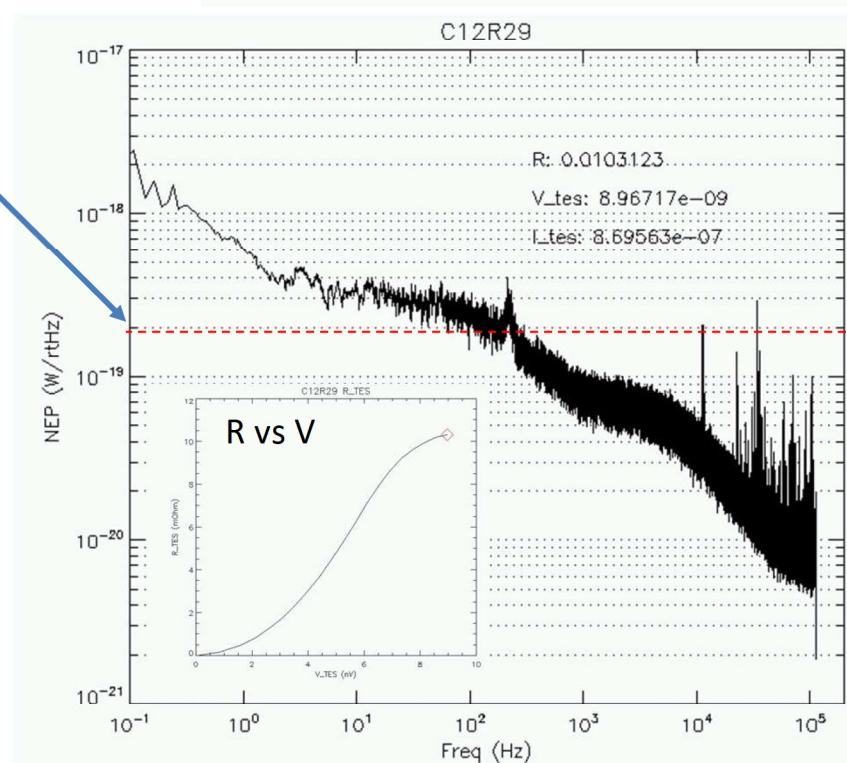
$\sim 6 \text{ pA/rtHz}$  floor



NEI vs Bias



NEP vs Bias



# Ir 2M device, MUX05

$T_c \sim 135$  mK

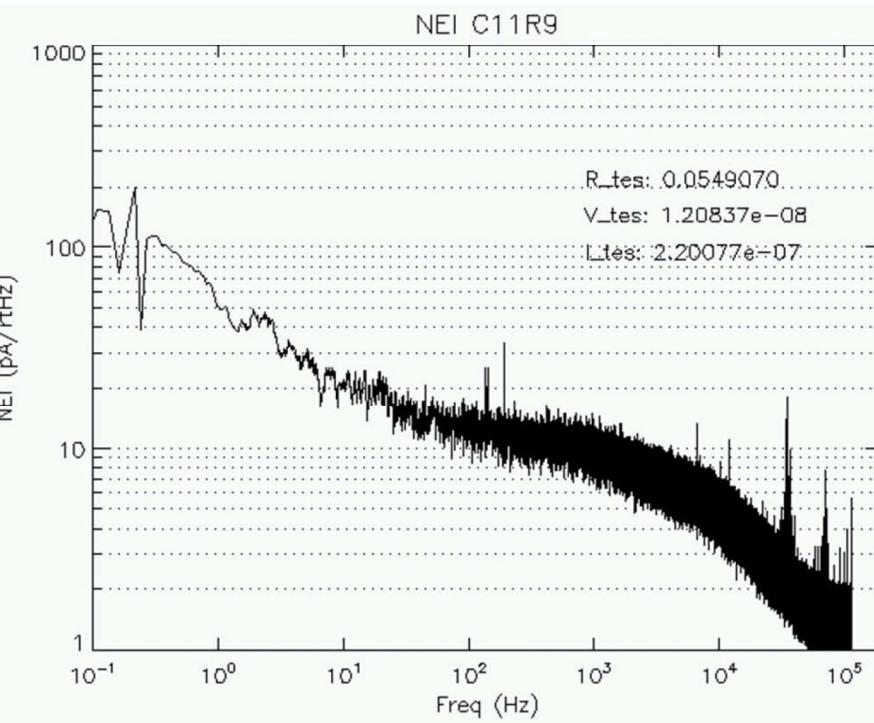
$G_c \sim 73$  fW/K

$\beta \sim 1.5$

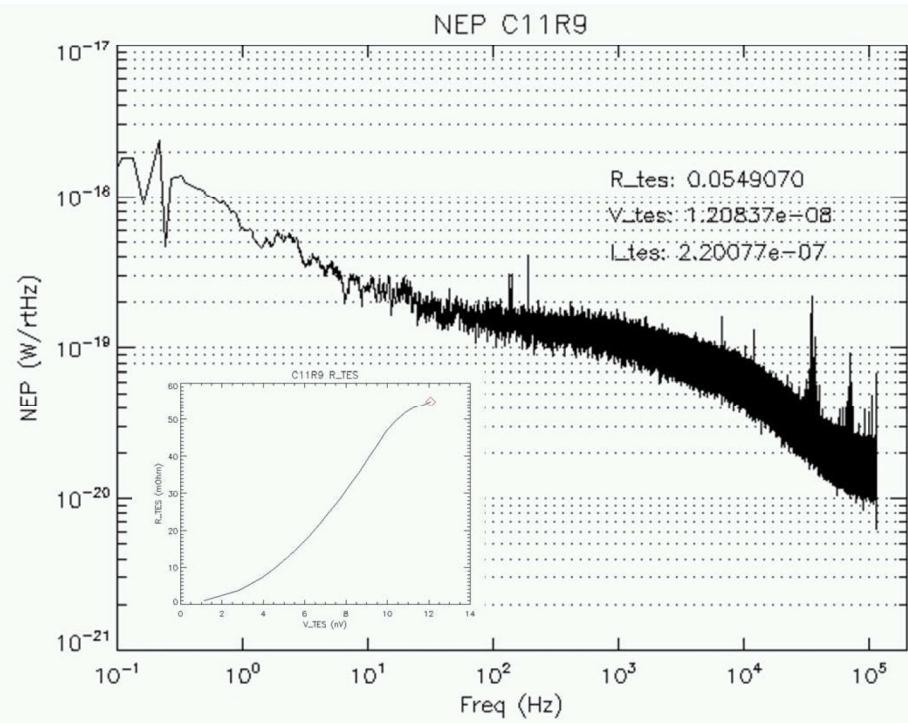
$R_n \sim 55$  mOhm

$NEP_G \sim 1.7E-19$  W/rtHz

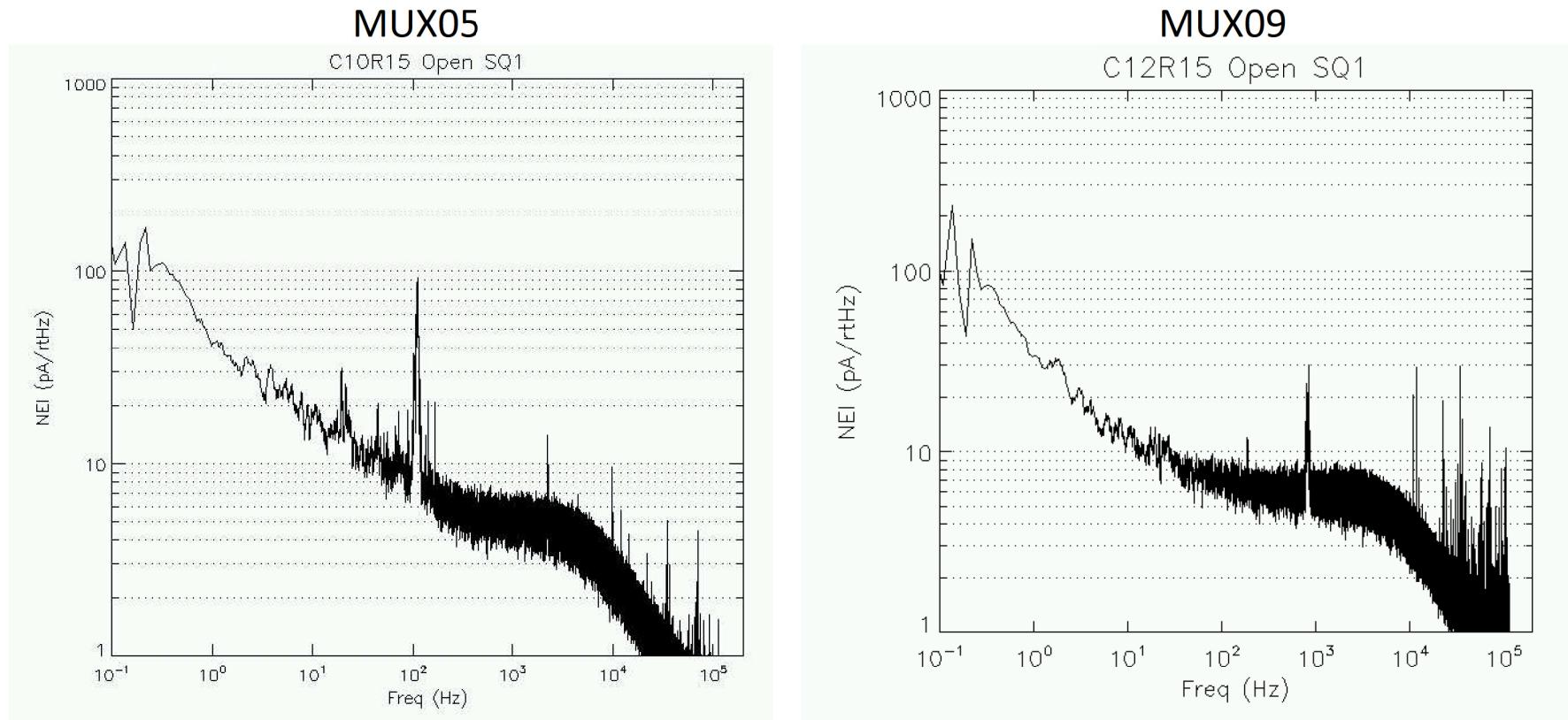
NEI vs Bias



NEP vs Bias



## Open SQ1 comparison for MUX05 vs MUX09:



1/f comes in at a bit higher frequency in MUX05, but noise level below 1 Hz doesn't appear to be much worse (ignoring huge spikes).

# Conclusions